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Paleomagnetism of upper Ediacaran clastics from the South Urals: Implications to paleogeography of Baltica and the opening of the Iapetus Ocean

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ABSTRACT

The progress in understanding the evolution of the Earth during the Ediacaran–Cambrian is greatly hindered by the scarcity and inconsistency of paleomagnetic data for this time interval. In order to acquire new data and clarify the confusing situation, Upper Ediacaran clastic rocks of the Basu Formation were sampled at several localities in the westernmost parts of the South Urals that is the deformed margin of Baltica at least since the beginning of the Neoproterozoic. With the aid of stepwise thermal demagnetization, a dual-polarity high-temperature component (HTC) was reliably isolated from gray and maroon sandstones and siltstones at 34/49 sites. The HTC mean direction D° = 55, inclination I° = −35 (k = 31, α_{95}° = 4.5) corresponds to a paleolatitude of 19° ± 3°. The reversal and fold tests are positive for the HTC. The slump test on two meter-sized slumps shows that the HTC predates slumping in one case and is coeval with it, in the other, thus convincingly indicating the primary origin of the HTC. Also, we demonstrate that inclination shallowing is either absent altogether, or, at worst, less than 10°, in these rocks; hence the position of Baltica can be reliably reconstructed for time 560–575 Ma. We reviewed paleomagnetic data with ages from 615 to 530 Ma for Baltica and Laurentia and come to the conclusion that there is still no uncontestable scenario for the opening of the Iapetus Ocean that is based on non-controversial geologic and paleomagnetic data.

1. Introduction

The Ediacaran–Early Ordovician interval is one of the most intriguing epochs of geologic time. The onset of the Ediacaran corresponds to the approximate end of the so-called "Snowball glaciations" and the terminal Ediacaran (~542 Ma) is followed by a great radiation of life forms commonly referred to as the "Cambrian Explosion". It has been argued that Ediacaran–Cambrian time period was also a time where continents underwent rapid changes in their latitudinal positions due to unusually rapid plate motions (Meert et al., 1993), inertial interchange true polar wander (Kirschvink et al., 1997), true polar wander (Evans, 1998) or interactions with superplumes (Meert and Tamrat, 2004). Abrajevitch and Van der Voo (2010) argue that the seeming complexities of continental motion in the Ediacaran–Cambrian are the result of the geomagnetic field switching between a dominant axial dipole field and an equatorial dipole field. These changes may be interrelated and connected, at least in part, to the distribution of continents across the globe.

The chief tool in deciphering paleogeography is paleomagnetism, and there are numerous attempts to provide a robust Ediacaran–Cambrian paleogeography using paleomagnetic data. Yet, it is precisely the Ediacaran–Cambrian time period (~635–488 Ma) where the paleomagnetic data are the most controversial (Meert et al., 1998; McCausland et al., 2007; Meert et al., 2007; Pisarevsky et al., 2008; Abrajevitch and Van der Voo, 2010; Meert, 2014). The problems are particularly acute for Laurentia and Baltica; most probably because they have the largest dataset.

There are very few, if any, Cambrian–Ediacaran targets on the platform of Baltica that are suitable for paleomagnetic studies and remain unstudied. However, there is a nearly thousand-kilometer-long band of Neoproterozoic and Ediacaran rocks in the western part of the South and Middle Urals along the Baltica margin (Fig. 1a). In particular, a nearly 2 kilometer thick Ediacaran terrigenous sequence is located in the South Urals (Stratotype of the Riphean: Stratigraphy, Geochronology, 1983; Bekker, 1988). These para-autochthonous units offer an opportunity to obtain new paleomagnetic data for the Ediacaran of Baltica. Because the units are considered to be para-autochthonous, the rocks must yield high-quality paleomagnetic results (including the age of the rocks) that can be evaluated for post-remanent rotations and translations with respect to the craton.

The western parts of the Uralian fold belt are similar to those of cratonic Baltica. In particular, a more than 10 km thick succession of

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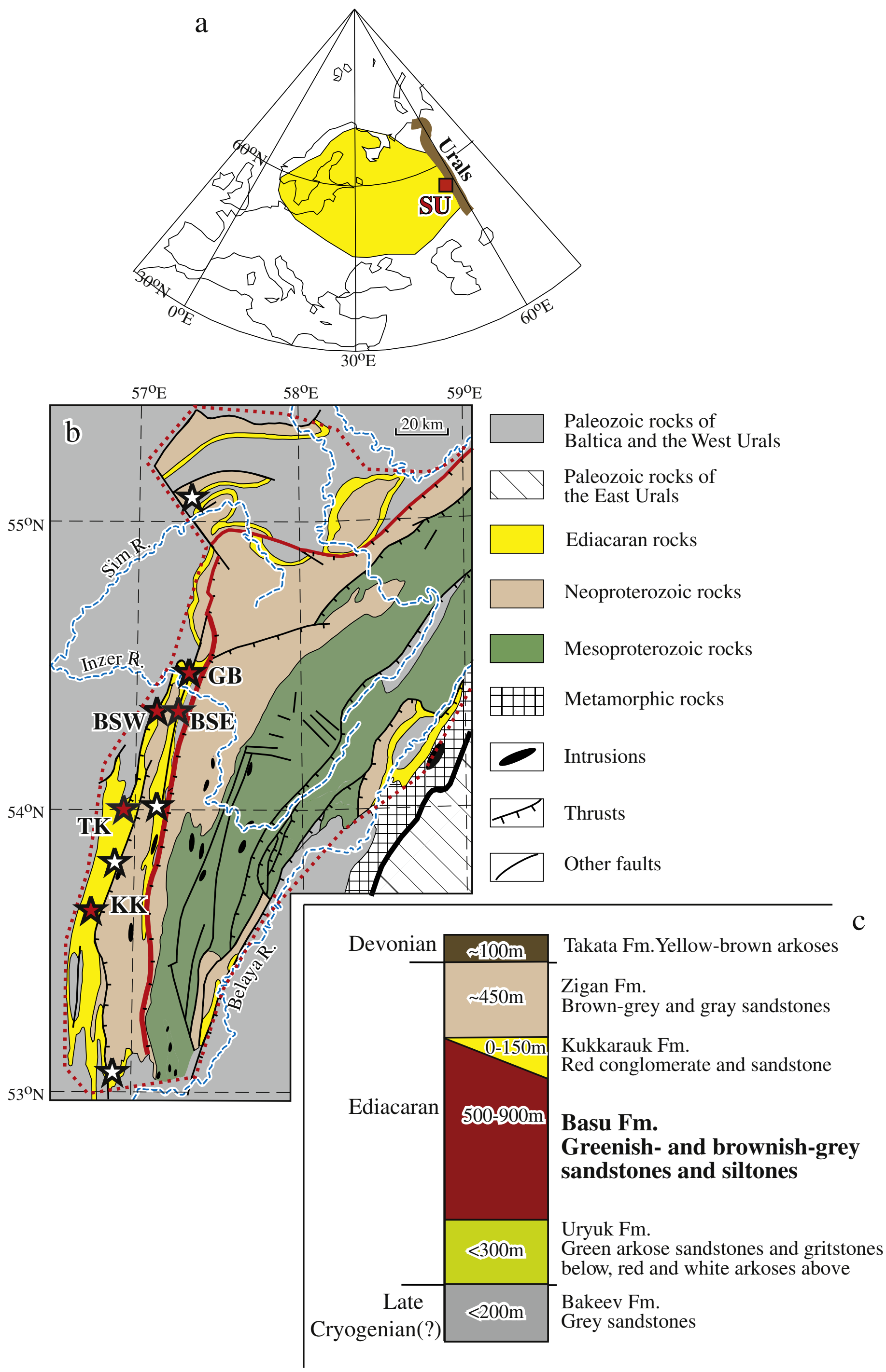

Fig. 1. (a) Location of the Baltica block with Precambrian basement (shaded), the Urals (brown band), and the study area in the South Urals (SU, red square). (b) Schematic map of the SW Urals with the limits of the Bashkir Anticlinorium (Uplift) shown as thick dotted line (simplified after Kozlov, 2002). The thickest red line denotes the Zilmerdak Fault, to the west of which Ediacaran rocks are overlain by Paleozoic rocks without angular unconformity. Thick black line is the Main Uralian Fault. Red stars denote the sampling localities numbered as in the text and Table 1, where the Upper Ediacaran Basu Formation was studied; white unlabeled stars denote localities, where no consistent results were obtained. (c) Simplified stratigraphic column of the Ediacaran sequence of the SW Urals.

Mesoproterozoic and Neoproterozoic mostly sedimentary rocks is exposed in the Bashkir anticlinorium (Uplift) in the western South Urals (Fig. 1b). This succession is reliably correlated with sections in the Ural Foredeep and the eastern parts of Baltica sensu stricto. Correlation is further supported by a series of matched seismic profiles (Stratotype of the Riphean: Stratigraphy, Geochronology, 1983; Puchkov et al., 2001). Although eastward-dipping seismic boundaries under the Bashkir Uplift are interpreted as the consequence of westward thrusting of the Uralian units over the craton in Permian time (Puchkov et al., 2001), the inferred transport along the thrusts is not considered to be significant. In light of this, these units are considered to be part of the Baltica deformed margin since the early Neoproterozoic (~1 Ga; Puchkov, 2003).

Exposed within the Bashkir Uplift is a nearly 10 kilometer thick succession of Mesoproterozoic and Neoproterozoic age clastic sediments and carbonates with subordinate Mesoproterozoic volcanics (Stratotype of the Riphean: Stratigraphy, Geochronology, 1983). The uppermost member of this succession, the Asha Series, comprises up to 2 km thick terrigenous clastics, presumably molasse (Bekker, 1988). It is divided into five members, the Bakeev, Uryuk, Basu, Kuk-Karauk and Zigan Formations in ascending order (Fig. 1c). The lower two units are predominately arkose, and the upper three formations are polymictic. Sandstone and siltstone prevail through the Series, with subordinate mudstone and rare gritstone.

There are no angular unconformities between the base of the Asha Series and mid-Permian rocks to the west of the Zilmerdak Fault (thick red line in Fig. 1b). Therefore, the only folding in the westernmost Urals took place in mid-Permian time (Kungurian, 272–279 Ma; Puchkov, 2003). Although Ediacaran rocks outcrop over a rather large area (Fig. 1b), the younger horizons of the Asha series with eastern dips are rare, being truncated by the regional Zilmerdak Fault. Consequently, most exposures of the Asha rocks have similar shallow dips to the west.

Until recently, the ages of the Asha Series and its members were not well constrained. The Asha Series para-conformably (and locally unconformably) overlies older Neoproterozoic rocks and is in turn para-conformably overlain by Middle Ordovician sediments in the south and Emsian (Early Devonian) sandstone elsewhere (Ivanushkin et al., 2009). A study of detrital zircons from the Kuk-Karauk Conglomerate and Basu Fm. Kuznetsov et al. (2012a,b, 2013) reveal a wide age range from >600 Ma to >2500 Ma and hence do not impose tight constraints on the age of the Asha Series. So far, the only isotopic age directly from the Asha Group (U–Pb method on zircons from a tuff bed) is that of 548.2 ± 3.5 Ma on the Zigan Fm. (Grazhdankin et al., 2011; Levashova et al., 2013). Ediacaran fossils were reported from several formations of the Asha Series, including the lowermost Bakeev Fm. (*Nemania Bakeevi* sp. nov.; *Beltanella zilimica* sp. nov.; *Intrites punctatus* Fed; *Incertae sedis* Bunyerichnus sp.; *Beltanelloides* (?) sp.) and the Basu Fm. (*Pseudorhizostomites howchini* Sprigg; *Protodipleurosoma paulus* Beck.; *Paliella patelliformis* Fed.; *Medusinites* sp.) (Bekker, 1992). Also found were some trace fossils: *Palaeopascichnus delicatus* Palij; *Neonereites uniserialis* Seilacher, *Catellichnus oktonarius* Becker (Bekker, 1992, 1996). Grazhdankin et al. (2011) and Ronkin et al. (2006) suggest a correlation between the Chernykamen Formation (Sylvitsa Group, Central Urals) and the Zigan Formation (South Urals) on the basis of Ediacaran fossils, sequence boundaries and geochronology. These correlations (and known U–Pb ages) would narrowly constrain the age of the Basu Formation to between 570 and 560 Ma (Ronkin et al., 2006; Grazhdankin et al., 2011; Maslov et al., 2013).

Several attempts to acquire paleomagnetic data on the terrigenous rocks of the Asha Series were undertaken and are summarized in Table 1 (the data based on incomplete demagnetization and not subjected to principal component analysis are excluded). The oldest Bakeev Fm. of presumed Late Cryogenian (Early Ediacaran) age is exposed in several locations (Stratotype of the Riphean: Stratigraphy, Geochronology, 1983) although no useful results were obtained from a pilot collection of samples collected by our research team.

The Uryuk Fm. is mostly composed of arkose gritstone and coarse-grained sandstones. The upper part of this formation comprises intercalating whitish and brick red medium-grained arkoses. Several sites yielded a component, which is directionally close to the widespread Late Paleozoic overprint in the Urals and was treated as such (Uryuk-red in Table 1).

500 to 900 meter thick greenish-gray and brown-gray sandstone with subordinate siltstone of the Basu Fm. were the subjects of several studies (Komissarova, 1963, 1970; Golovanova et al., 2011; Iosifidi et al., 2012). A dual-polarity remanence with northeastern declination and negative inclination was reliably identified by all researchers (Basu-1 in Table 1) and was considered a mid-Paleozoic prefolding overprint by Iosifidi et al. (2012). These authors have also isolated another bi-polar component (Basu-2 in Table 1) in five samples out of 30 studied and claimed it to be primary.

The most complicated dataset comes from the Kuk-Karauk Fm. that comprises mostly reddish-brown coarse-grained sandstones, often with millimeter-sized floating pebbles, and a regionally traceable conglomerate unit (Kuk-Karauk Conglomerate). This unit is up to 50 m thick in the south of the Bashkir Uplift, thins out to a few meters in its central part and wedges out altogether further to the north. Most pebbles are made of white quartz; with subordinate granites, black volcanic rocks, red cherts, and sometimes reddish sedimentary rocks. Pisarevsky et al. (1999) obtained scattered component directions from 33 samples of medium grained sandstones both below and above the conglomerate at two localities but claimed the presence of three dual-polarity components after sorting the data with the aid of cluster analysis (Kuk-Karauk-1 to Kuk-Karauk-3, Table 1). Iosifidi et al. (2012) studied 70 samples from three localities and recognized two dual-polarity components, both of which agree with their results on the Basu Fm. We studied 34 samples from five sites at two localities and found a dispersed cloud ($k \sim 2$) of high-temperature component (HTC). All in all, the presence of any consistent component does not appear to be established in this formation. Finally, Golovanova et al. (2011) sampled thirty cobbles of magmatic rocks and sediments from the Kuk-Karauk Conglomerate, most of which yielded a well defined and rather tightly grouped single component aligned with the present-day field.

The youngest member of the Asha Series, the Zigan Fm., yielded a well-defined dual-polarity remanence in maroon sandstones at three localities (Levashova et al., 2013).

Table 1
Summary of paleomagnetic results on the Asha Series.

Formation & datum	n	CS	D°	I°	k	α_{95}°	Ref.
Bakeev	15	No consistent components are isolated					Unpublished data
Uryuk-green	40	No consistent components are isolated					Unpublished data
Uryuk-red	(6)	60%	245	−37	29	13	Levashova et al. (2013)
Basu-1	(17)	S	55	−37	39	6	Golovanova et al. (2011)
Basu-2	5[?]	S	153	−23	18	18	Iosifidi et al. (2012)
Kuk-Karauk-1	?	S	344	−8	18	8	Pisarevsky et al. (1999)
Kuk-Karauk-2	?	S	39	84	9	10	Pisarevsky et al. (1999)
Kuk-Karauk-3	?	S	245	−7	9	9	Pisarevsky et al. (1999)
Kuk-Karauk-4	9[?]	S	46	−40	22	11	Iosifidi et al. (2012)
Kuk-Karauk-5	18[?]	S	153	−14	24	7	Iosifidi et al. (2012)
Kuk-Karauk-6	35(5)	Very scattered data					Unpublished data
Kuk-Karauk Congl.	29	G	343	68	12	8	Golovanova et al. (2011)
Zigan	(37)	S	106	−16	25	5	Levashova et al. (2013)

Comments. Formation & datum is the formation name and the label of a paleomagnetic result as defined in the text. n, is the number of samples (sites) [localities] used; question marks denote the cases where the level of statistics and/or distribution of samples between sites and localities are unknown. Unpublished data are obtained by the authors of this paper but are not published separately. CS, coordinate system, which the results are presented in: S, stratigraphic, G, geographic, and 60%, after 60-percent unfolding. D, declination. I, inclination. k, concentration parameter. α_{95}, radius of 95% confidence circle (Fisher, 1953).

Here we present new paleomagnetic results from the Basu Fm. and examine the implications of these results for Ediacaran paleogeography.

2. Sampling

The 500 to 900 meter thick Basu Fm. comprises about half of the Asha Series (Fig. 1c). Within a ~30–40 meter thick transitional zone, red arkoses of the underlying Uryuk Fm. are gradually replaced with darker colored polymictic sandstones of the Basu Fm. Its upper boundary is imprecisely defined by gradual transition to predominantly brown red and generally coarser sandstones of the Kuk-Karauk Fm. (Fig. 1c). The sections of the Basu Fm. vary laterally, but have no regionally recognizable marker horizons; this and limited patchy exposures along river beds and roads lead to a situation that even sections a few kilometers apart cannot be unambiguously matched.

The Basu Fm. mainly consists of fine- to medium-grained polymictic sandstones, with subordinate siltstones and millimeter-thick argillite films on bedding surfaces of coarser-grained varieties. Most sandstones and siltstones are gray to greenish-gray, sometimes maroon, whereas argillites are usually chocolate-colored, thus often making the outcrops look like red beds. The rocks are non-metamorphosed; even calcite veins are rare. Cross-bedding, ripple marks, sometimes slumps, testify to the accumulation of the Basu rocks at shallow water depths. The polymictic part of the Asha Series, including the Basu Fm., is regarded as molasse by Bekker (1988). The scarcity of coarse-grained rocks points to accumulation in distal parts of a molasse basin.

We sampled the Basu Fm. at several localities that are spread over more than 100 km from north to south (red stars in Fig. 1b). Locality GB is at the northern periclinal section of the Avdyrdak Anticline where it is cut by the Inzer River. This locality provided us with six sites from adjoining sections along with a slump fold that was several decimeters in length. Localities BSW and BSE are sampled from road cuts in the Basu River valley where it crosses the western and eastern limbs, respectively, of the same fold. Twenty-three sites that are spread over a considerable part of the formation thickness were studied. Three sites were collected along the eastern bank of the Takata River (Locality TK). At locality KK (in the Kuk-Karauk valley) a total of 17 sites and two slump folds were sampled (see more detail below). The remaining sites yielded numerous samples, but no interpretable data (white stars in Fig. 1b).

3. Paleomagnetism

3.1. Methods

Paleomagnetic samples were collected as hand-sized blocks oriented with a magnetic compass, one sample being taken at a stratigraphic level. Four to twelve or even more samples collected from a 3 to 10, sometimes up to 30 m thick section parts, depending on the exposure quality and the availability of suitable rock varieties, is considered a site. Cubic specimens of 8-cm^3 volume were cut from each hand sample. The collection was studied in the Paleomagnetic laboratories of Geological Institute of the Russian Academy of Sciences in Moscow and at the Institute of Geology (Ufa Scientific Center, Russian Academy of Sciences) in the city of Ufa. Individual specimens were stepwise heated in 12 to 20 increments up to 700 °C in either homemade ovens (Moscow) or utilizing an Analytical Services TD-48 thermal demagnetizer with internal residual fields of <10 nT (Ufa); measurements of the natural remanent magnetization, NRM, were done with a JR-4 or JR-6 spinner magnetometer with a noise level of 0.05 mA/m. Demagnetization results were plotted in orthogonal vector diagrams (Zijderveld, 1967). Visually identified linear trajectories were used to determine directions of magnetic components by Principal Component Analysis (PCA), employing a least-squares fit comprising three or more demagnetization steps (Kirschvink, 1980), anchoring the fitting lines to the origin where appropriate. Paleomagnetic software written by Jean-Pascal Cogné (2003) was used in the analysis.

3.2. Results from the main collection

The NRM values in the Basu rocks range from less than 1 mA/m to nearly 100 mA/m. In contrast, susceptibility values are uniformly low, below 0.5 mSI units in most samples (Komissarova, 1970). Stepwise thermal demagnetization revealed that the NRM could be accounted for by up to three components in varying proportion. A low-temperature component (LTC) was removed between 200 and 300 °C and may dominate in samples with low NRM values. The LTC directions are scattered at some sites or gravitate toward the present-day field direction. Thus, this component is likely a recent viscous overprint and is excluded from further analysis.

After removal of the LTC, an intermediate-temperature component, ITC, is present (Fig. 2a–b) in many cases. The ITC directions are scattered, with the exception of site BSW10 (Fig. 2b–c), where the ITC is adequately clustered with a mean direction in situ (D° = 243.8, I° = −39.3, α_{95}° = 13.2°, n = 8 samples). This direction is similar to the regional mean of the Permian overprint (D° = 230.0, I° = −40.7, α_{95}° = 8.7; Levashova et al., 2013).

In approximately half of the collection, no ITC is observed and a single well-defined high temperature component (HTC) shows a rectilinear decay to the origin (Fig. 2d–f). In samples with an ITC component, the HTC component can also be reliably isolated (Fig. 2a–b). It seems that the same HTC is present in the samples of Basu rocks, irrespective of the differences in demagnetization characteristics. It is worth noting that there are no samples with the HTC bypassing the origin and revealing a remanence of opposite polarity. The HTC is mostly unblocked between 580° and 700° (Fig. 2) and resides in hematite. Optical studies indicate that hematite grains are widespread in the Basu rocks (Kozlov, 1982). Rock magnetic studies of the Basu rocks confirm that hematite, sometimes with traces of magnetite, is the main remanence carrier (Komissarova, 1963, 1970; Iosifidi et al., 2012). This conclusion is valid for all rock varieties, and the samples of very similar color and grain size may have the single HTC, both HTC and ITC, or no stable component at all. Dark maroon and purely gray samples may yield similar HTC directions.

HTC directions are acceptably grouped at 34 sites of 49 studied (Fig. 3a–b; Table 2). The fold test (McElhinny, 1964) is positive (k_{TC}/k_{IS} = 5.15; 95% critical value is 1.51), maximum data grouping is at 100% unfolding. Some site-means, however, are rather poorly defined, and the same test was repeated for better defined 24 sites with α_{95} < 15°. Using the more restrictive dataset, the fold test was also positive (k_{TC}/k_{IS} = 6.45; 95% critical value is 1.63) (Fig. 3d). The positive fold test only constrains the age of magnetization to older than the mid-Permian (Puchkov, 2003). We note that the mean from sites with α_{95} > 15° and the mean from sites with α_{95} < 15° are statistically similar (called *imprecise* and *precise*, respectively; Table 2). We conclude that the lower precision data stem from poor averaging of internal scatter rather than from contamination by another remanence. Note also that the HTC directions are statistically similar over more than 100 km (Fig. 1b, Table 2) that negates local rotations between sampling sites.

The HTC reveals a dual-polarity magnetization (Figs. 2 and 3). At four sites, where relatively thick intervals were sampled, both polarities are found in several adjacent samples; such one-polarity intervals are treated as separate sites (Table 2). The HTC directions form two distinct polarity clouds at both site-mean and sample levels after tilt correction. The reversal test is "double" positive: the scatter of normal and reverse sites is statistically identical (k_N = 50.3, k_R = 47.8), and the polarity means are antipodal: the observed angle between them (inverted to one polarity) is much less than the critical one (γ_{obs} = 3.8°, γ_{crit} = 8.8°; class B; McFadden and McElhinny, 1990). The test is also positive at the sample level (k_N = 15.9, k_R = 14.9; γ_{obs} = 2.8°, γ_{crit} = 5.4°). Note that there is no trace of the Basu 2 component (Table 1) that was

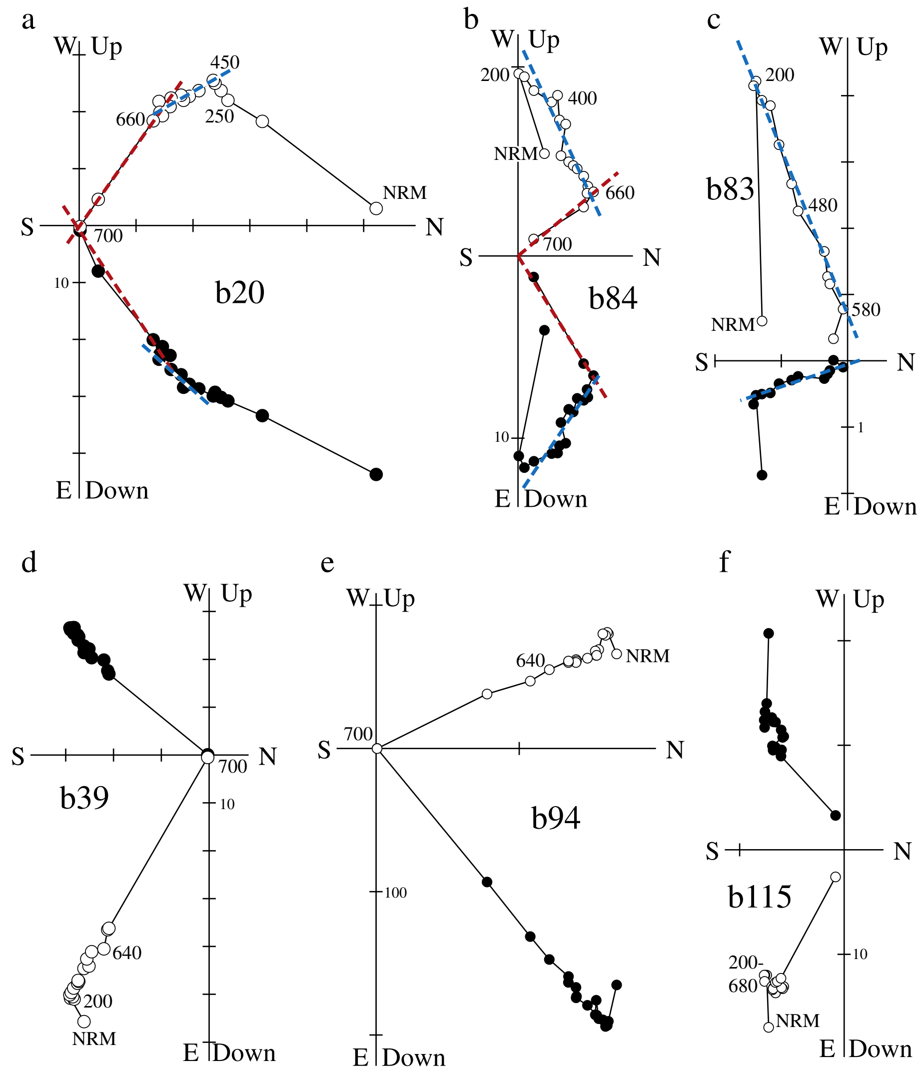

Fig. 2. Representative thermal demagnetization plots of the Ediacaran Basu Formation from the western part of the South Urals, in stratigraphic coordinates. Isolated intermediate-temperature (blue) and high-temperature (red) components are denoted by thick dashed lines. Temperature steps are in degrees Celsius. Magnetization intensities are in mA/m. Full (open) circles represent vector endpoints projected onto the horizontal (vertical) plane.

claimed to be of primary origin by Iosifidi et al. (2012), among our nearly two hundred HTC sample directions (Fig. 3c).

3.3. Results on slump folds and the origin of the high-temperature component

We sampled three slumps at different localities. In the lower part of the KK section, slump 1 is exposed in an ~2.5 m high wall of an abandoned small quarry that was used for road construction. In some places (gray spots in Fig. 4a), the rocks are strongly fractured, most probably during the quarry being in use. Slump 2 is found in the natural outcrop in the upper part of the KK section (Fig. 5a). Some fifteen samples were taken from each slump, mostly from fine-grained platy sandstone, and a standard site of 7–8 samples was taken from non-deformed beds close to each slump. Bedding was separately measured for each sample from the slumps; this was facilitated by platy character of sandstones that show the strongest degree of slumping. Finally, both slump 3 and host rocks at locality GB did not yield stable components.

Demagnetization characteristics are very similar for deformed and non-deformed rocks (Figs. 4b–d, 5b–d) and also similar to those for the Basu rocks in general (Fig. 2). The grouping of HTC data at two non-deformed sites is reasonably good, and the corresponding site-means agree with the other HTC directions after tilt correction (Tables 2 and 3). Thus we conclude that the remanences in non-deformed rocks near the slumps and in the main body of the Basu Fm. are of the same origin.

In slump 1, from the lower part of the KK section, the HTC directions are significantly better grouped after tilt correction, and the best data grouping is achieved after 100% unfolding although the overall scatter remains rather high (Fig. 4e–g). In slump 2, the best data grouping is achieved at 55% of unfolding (Fig. 5e–h). Moreover, the slump mean is displaced both from the mean for the adjacent site (Fig. 5e–f) and main dataset (Fig. 3b).

The fold test in paleomagnetism is based on an assumption that each fold limb rotates as a rigid body about a horizontal axis. When slumping in a pliable bed occurs very soon after deposition, this assumption is invalid. Hence the perfect alignment of paleomagnetic vectors is unlikely even if the remanence predates slumping. Moreover, the slumped block may be displaced as the whole, which is likely what happened with slump 2. Thus, the HTC is older than slumping in the first case, while it appears to be coeval with deformation in the second. These slump-test results provide strong evidence for a primary remanence in the Basu Fm.

In sum, the positive fold and reversal tests and two slump tests indicate that the remanence was acquired very close to the age of

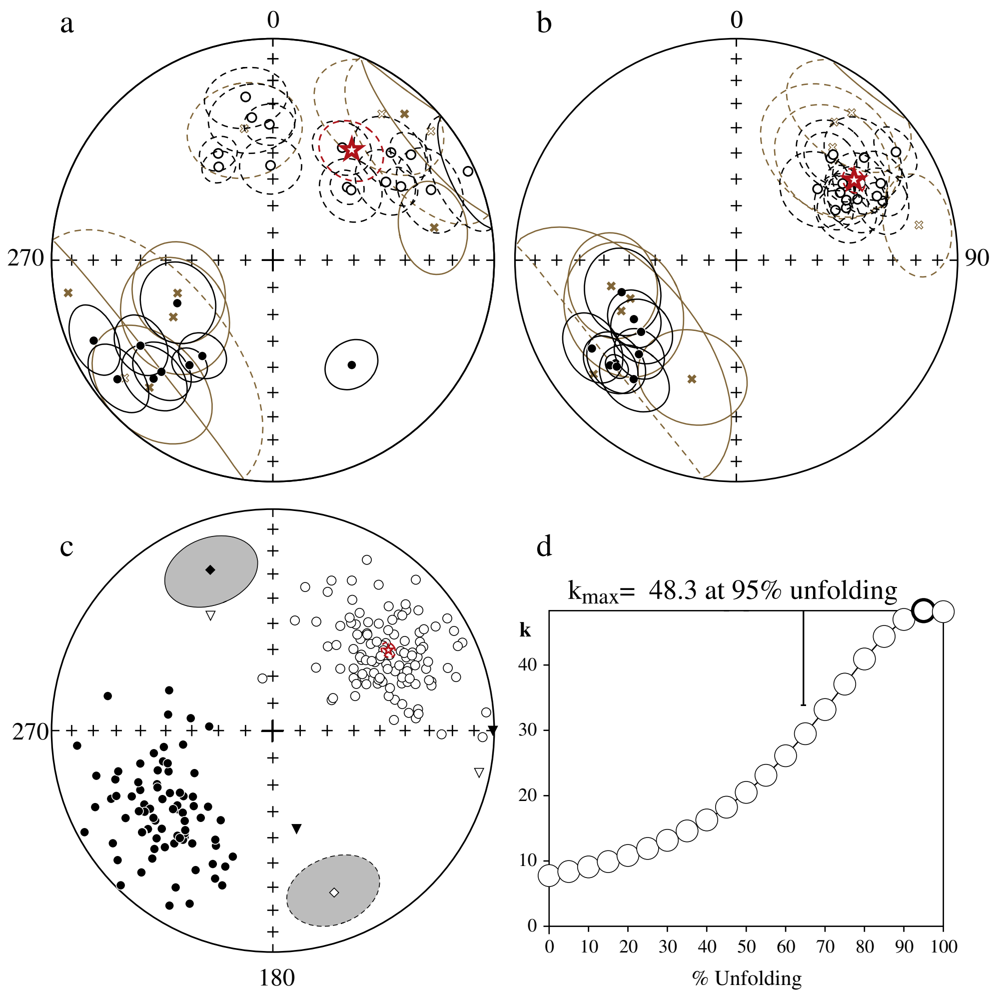

Fig. 3. (a–b) Stereoplots of high-temperature component, HTC, site-mean directions in the late Ediacaran clastic rocks of the Basu Fm. in situ (a) and after tilt correction (b). Black (brown) symbols and lines denote the sites with confidence circles of <15° (>15°). Stars are the overall mean directions with associated confidence circles (thick lines) for the sites with confidence circles of <15°. (c) Stereoplots of HTC sample directions in the same rocks after tilt correction: circles, accepted for calculation of site-means, inverted triangles, discarded as anomalous. Star is mean direction for accepted samples. Diamonds and shaded circles are mean directions and confidence circles for a high-temperature component that is claimed by Iosifidi et al. (2012) to be present in the Basu rocks (see text for detail). Full (open) symbols and solid (dashed and dotted) lines are projected onto lower (upper) hemisphere. (d) Plot of concentration parameter k versus stepwise unfolding for the sites with confidence circles of <15°. Solid vertical line denotes 95% confidence level.

deposition. In spite of this evidence for a primary remanence, it should be noted that the Basu pole falls close to the Late Ordovician–Silurian segment of the apparent polar wander path (APWP) for Baltica. This similarity was noted decades ago (Komissarova, 1970) and confirmed by recent studies (Golovanova et al., 2011). In the latter paper, the remagnetization hypothesis was analyzed, but could not be rejected as a possible explanation for the similarity in direction. Given the positive slump tests in our study, we conclude that the agreement between the APWP for Baltica and the Basu pole is fortuitous, and the dual-polarity HTC in the Basu rocks is primary.

4. Inclination shallowing

Inclination shallowing was discovered many decades ago (King, 1955) but was thought to be relatively uncommon. In the 1990's evidence began to mount that inclination shallowing is more widespread in fine-grained red beds and sparked a renewed interest in analytical and experimental techniques aimed at identifying the problem. Detection of inclination shallowing remains cumbersome and labor-intensive, while correcting for inclination shallowing was, and still is, a tricky business (Sun and Kodama, 1992; Tan and Kodama, 2002). In an effort to simplify both detection and correction of inclination shallowing, the elongation–inclination test was regarded as a major break-through and is widely utilized (Tauxe and Kent, 2004; Tauxe, 2005). There are, however, several points that may affect the validity of this approach:

1. Tauxe and Kent (2004) used a model of the geomagnetic field based on observations over the past 5 Ma. While the 0–5 Ma field data are fairly robust, the model has not been validated for earlier periods in Earth history and even during that interval, the fit of model predictions to observations often shows large discrepancies (Johnson et al., 2008).
2. The elongation of a paleomagnetic distribution is a statistical parameter that becomes acceptably “steady” for large datasets only. Tauxe and Kent (2004) recommend a minimum of 100 site means are required for proper analysis. This level of sampling density is seldom achieved with the exception of a series of thick lava flows.
3. The scatter of observed directions, especially in sediments, is due not to secular variation alone but to its sum with paleomagnetic noise from other sources. Hence, the distributions of paleomagnetic data may be more circular than predicted by the TK-model.
4. The correction for inclination shallowing is performed with the bootstrap that gives biased, often strongly biased (see Fig. 5 in Tauxe et al., 1991), estimates for all parameters that are not normally distributed.

Table 2
High-temperature component directions in clastic rocks of the Basu Formation.

Id	S/d	n	In situ				Tilt-corrected			
			D°	I°	k	α_{95}°	D°	I°	k	α_{95}°
Gabdukovo Village, 54.4°N, 57.2°E										
GB3-1	347/18	11/10	232.6	12.6	19.6	11.2	229.5	29.1	21.0	10.8
GB3-2	341/22	4/4	66.0	−22.8	46.5	13.6	64.6	−44.2	59.3	12.0
GB		(6/2)	59.1	−17.8	–	–	56.3	−36.9	–	–
Basu River, eastern limb, 54.3°N, 57.3°E										
BSE5	329/35	4/3	231.5	−15.6	8.3	45.9	231.4	18.6	8.2	46.3
BSE6-N	4/35	3/3	50.8	−8.7	19.8	28.5	40.5	−33.5	26.0	24.7
BSE6-R	4/39	6/6	245.8	12.3	40.9	10.6	233.0	45.3	34.8	11.5
BSE7	4/42	6/5	224.2	21.0	14.0	21.2	200.5	42.2	17.7	18.7
BSE9	12/45	4/2	261.0	7.0	–	–	250.1	47.8	–	–
BSE10	357/44	10/9	78.6	26.5	13.3	14.7	79.1	−17.1	12.2	15.4
BSE19	7/64	4/2	42.0	12.1	–	–	35.4	−24.6	–	–
BSE20	2/54	5/5	65.5	−3.5	22.1	16.6	48.8	−49.6	32.1	13.7
BSE		(13/8)	59.8	0.2	13.9	15.4	50.1	−36.1	16.2	14.2
Basu River, western limb, 54.3°N, 57.1°E										
BSW10	197/63	12/6	351.6	−35.2	23.0	14.3	42.6	−35.5	27.8	12.9
BSW11	206/68	9/9	358.5	−38.6	39.0	8.4	58.3	−34.3	24.9	10.5
BSW12	210/78	7/7	350.5	−26.2	23.0	13.0	54.3	−40.5	91.1	6.4
BSW13	194/63	10/5	347.7	−39.1	16.7	19.3	44.2	−36.9	14.4	20.8
BSW16-1	194/78	9/7	143.0	40.4	42.7	9.3	240.1	45.6	36.3	10.1
BSW		(10/5)	346.7	−36.5	44.8	11.6	51.7	−38.8	109.2	7.4
Takata River, 54.0°N, 56.9°E										
C247	197/67	7/7	358.6	−54.8	31.9	10.8	68.0	−29.4	31.9	10.8
P1644	196/72	8/8	332.9	−45.0	71.2	6.6	61.4	−42.8	43.7	8.5
P1652	196/65	8/8	329.8	−49.7	86.9	6.0	63.3	−48.5	66.1	6.9
TA		(3/3)	339.5	−50.5	54.7	16.8	64.5	−40.3	64.1	15.5
Kuk-Karauk Brook, 53.6°N, 56.7°E										
KK1R	212/10	10/10	225.0	29.5	22.1	10.5	230.2	26.7	24.1	10.0
KK1N	215/7	6/6	47.7	−28.6	27.2	13.1	51.3	−26.8	22.5	14.4
KK2	14/10	10/10	225.2	25.0	18.0	11.7	220.8	29.8	16.4	12.3
KK3	214/10	6/5	245.8	50.9	29.3	14.4	254.4	45.3	27.0	15.0
KK4	207/7	6/6	240.3	47.0	11.4	20.7	246.2	42.6	9.2	23.3
KK5	177/6	6/6	237.1	29.5	43.5	10.3	238.6	24.5	34.2	11.6
KK6	190/5	6/5	36.7	−18.8	13.4	21.7	38.1	−16.6	14.4	20.9
KK8R	197/13	7/6	251.0	52.4	15.0	17.9	258.3	41.8	15.0	17.9
KK8N	206/14	7/6	31.7	−40.1	43.1	10.3	42.8	−37.3	50.8	9.5
KK9	195/13	11/11	45.6	−51.1	54.8	6.2	57.0	−43.4	58.5	6.0
KK10	187/18	7/7	218.5	39.3	92.4	6.3	228.3	28.5	209.4	4.2
KK11	190/13	8/7	216.4	45.3	51.0	8.5	226.0	38.8	44.8	9.1
KK13	193/13	6/6	52.7	−22.6	77.6	7.7	55.9	−13.9	68.0	8.2
KK14	187/14	6/5	56.1	−37.8	46.1	11.4	61.6	−26.7	51.8	10.7
C100*	224/9	7/7	60.1	−33.7	85.0	6.6	65.5	−30.8	184.2	4.5
C107*	198/19	8/8	48.2	−50.8	24.0	11.5	63.3	−38.7	25.0	11.3
KK		(17/16)	49.3	−38.1	33.5	6.5	55.5	−32.5	35.9	6.2
ALL**		(49/34)	41.1	−31.9	6.2	10.8	54.8	−34.7	31.1	4.5
Precise**		(24)	36.1	−38.2	7.8	11.4	55.9	−35.3	47.8	4.3
Imprecise**		(10)	51.4	−14.9	5.4	23.0	52.1	−33.3	15.9	12.5
LOCs**		[5]	33.2	−33.3	4.6	40.0	55.7	−36.7	215.8	5.2
Precise – mean pole: n = (24) Plat = 1.7°N, Plong = 186.1°E, K = 62.5, A_{95} = 3.8°										

Comments. Localities are labeled as in Fig. 1b; ALL is the overall mean for all sites listed in the table; Precise/Imprecise is the mean for all sites with $\alpha_{95} < 15°$ ($\alpha_{95} > 15°$); LOCs is the mean for five locality-means, each of which is calculated for all sites from the locality. S/d is the mean strike and dip for the site. n, number of samples (sites) [localities] studied/used. Mean pole is computed by averaging site-mean virtual geomagnetic poles: Plat, pole latitude; Plong, pole longitude; K concentration parameter, A_{95}, radius of 95% confidence circle. Other notation as in Table 1.

* These sites are close to two slump folds that are discussed separately.

** These means are computed by recalculating all site-means and locality-means to the common point at 54.3°N and 57.3°E.

In particular, elongation parameter has a clearly non-Gaussian distribution, and thus its estimates can be strongly biased.

Thus while the E-I method may prove useful in some younger studies, the limitations noted above preclude its blanket use as a corrective measure. An alternative may be the use of qualitative tests to determine if shallowing is present. In a purely geometric sense, inclination shallowing will affect the distribution of paleomagnetic data by transforming a circular or near circular distributions into a banana-like distribution with elongation in the east–west direction (Bazhenov, 1981; Tauxe, 2005). Hence the presence of strong inclination shallowing can be established by observation if the banana-like elongation is present and statistically significant.

In our case, the number of acceptable Basu sites (Table 2) is too limited for the E-I method. We compiled sample directions from the sites, where consistent HTC data are recovered from all or most samples (Fig. 3c, Table 4). As the samples are stratigraphically ordered at each site, each unit vector represents a spot reading of the field, albeit an imprecise one. The pre-shallowing form of the distribution can be reconstructed by stepwise varying the shallowing parameter f in the formula: $\tan I_m = f * \tan I_o$, where I is inclination (°), subscripts m and o stand for measured and original values, respectively, f may vary from

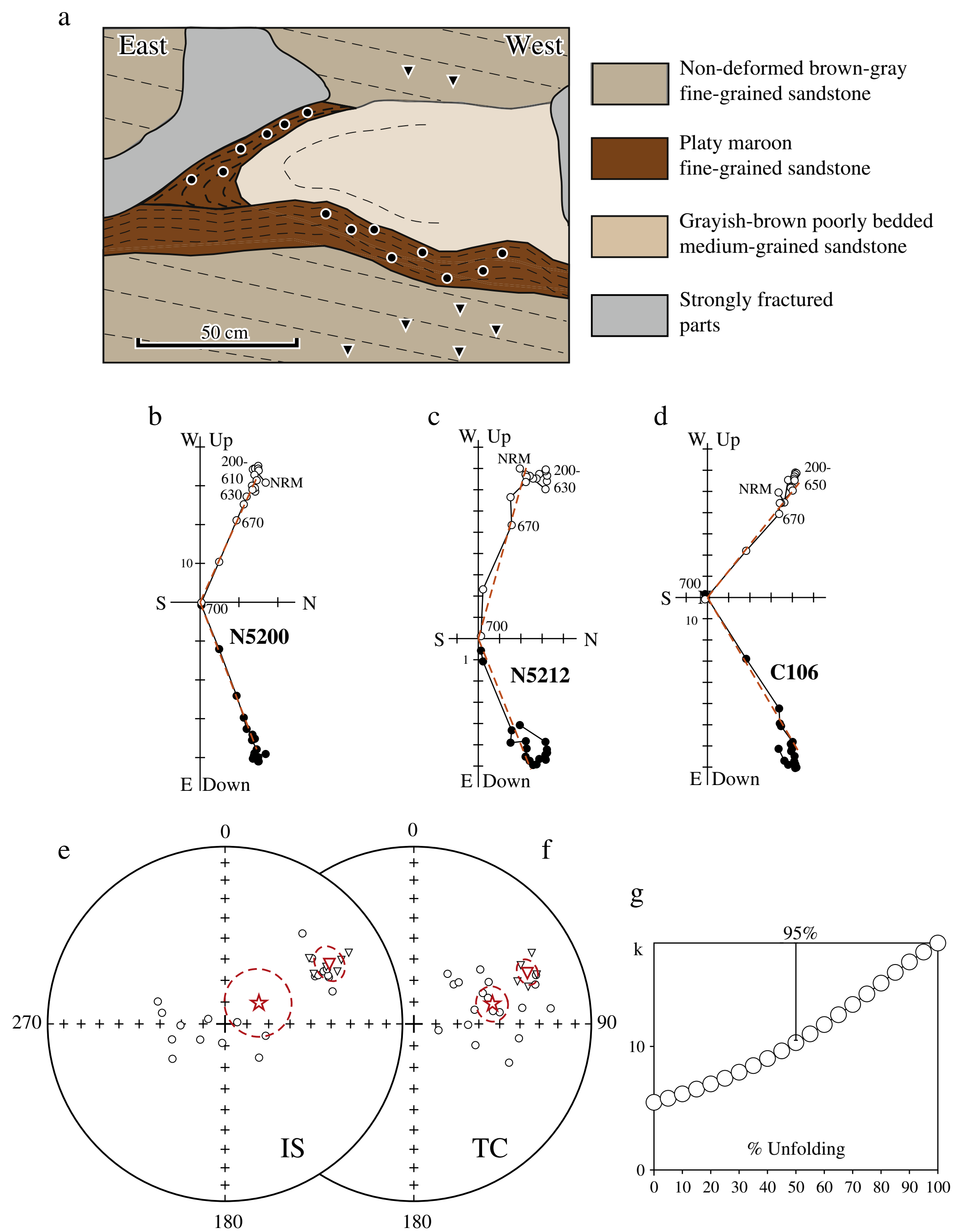

Fig. 4. (a–c) Representative thermal demagnetization plots of samples of the Ediacaran Basu Formation from slump-1 (b–c) and non-deformed rocks (d) in stratigraphic coordinates. Isolated high-temperature components are denoted by thick dashed red lines. Other notation as in Fig. 2. (e–f) Stereoplots of high-temperature component, HTC, in the samples from the slump (circles) and non-deformed rocks (inverted triangles) in situ (e) and after tilt correction (d). Star (large inverted triangle) is overall mean direction with associated confidence circle (thick line) for the slump samples (non-deformed rocks). Other notation as in Fig. 3. (g) Plot of concentration parameter k versus degree of unfolding for the slump samples only. Solid vertical line denotes 95% confidence level.

1 to 0. After each step, we calculated an elongation parameter E value after Tauxe (2005) and a best-fitting great circle that denotes the long axis of distribution. The latter must pass close to the projection pole (deviation of the great circle from the pole, ΔGC, is close to zero) if a distribution is elongated in vertical plane as predicted by the model of Tauxe and Kent (2004). In other words, the declination of the point where this great circle crosses the stereonet equator must coincide with the mean declination for the dataset in this model. In contrast, this great circle must deviate from the projection pole with ΔGC° ~ $(90 - I_m)$ for shallowed data. Note also that, to be statistically significant, the observed elongation must exceed the 95% critical value for this parameter; for 195 vectors used in analysis, the latter value is ~1.30.

For the original dataset, i.e., for $f = 1.0$ (Fig. 6a, Table 4), the unit vectors form a well-defined cloud of nearly circular outline, E is statistically insignificant and much less than the value predicted by the TK-model. ΔGC of 40.5° is large but significantly less than the predicted value of ~54° for shallowed data. Hence this distribution is axially

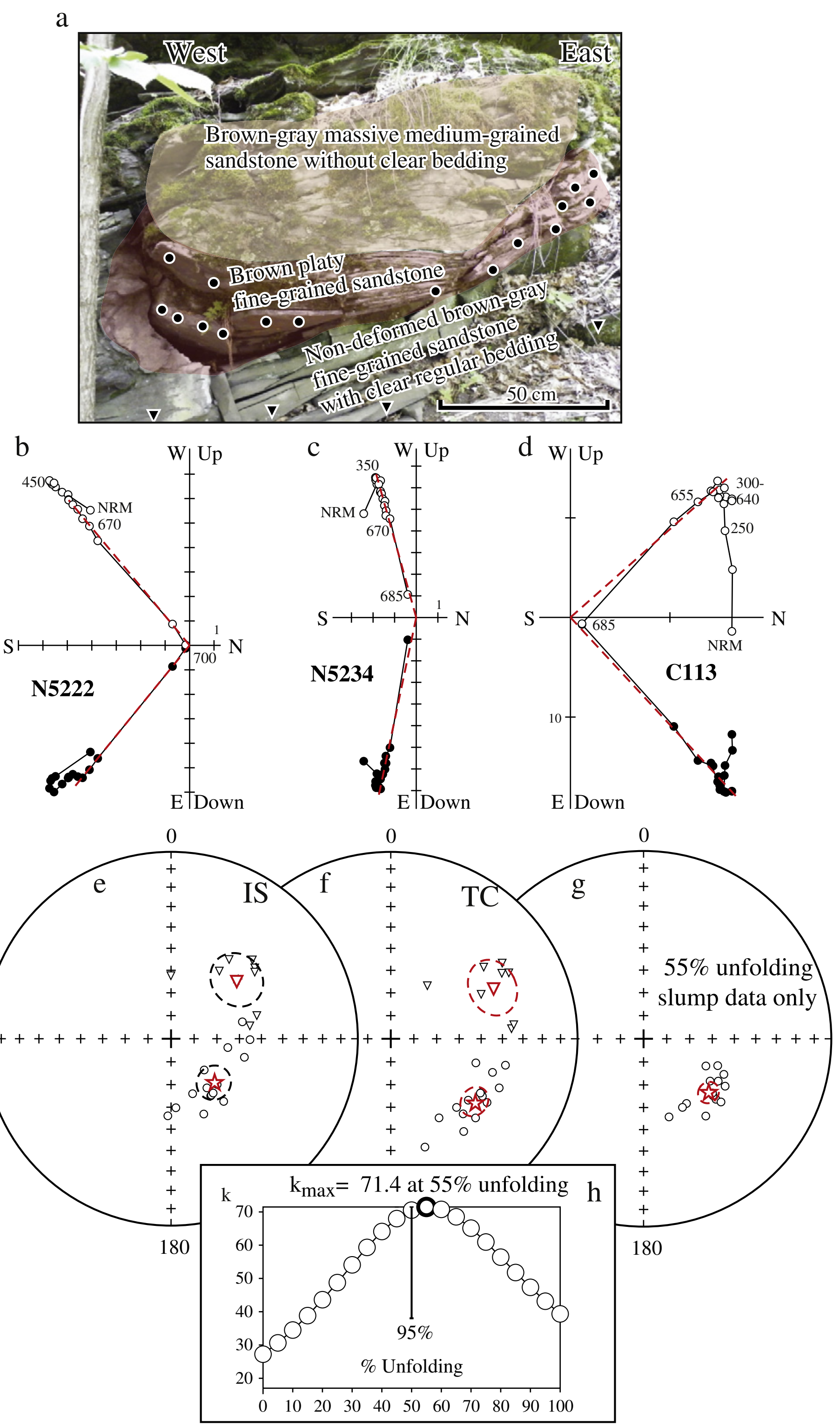

Fig. 5. Picture of the sampled slump-2 and paleomagnetic data. (a) Picture of slump-2. Circles (inverted triangles) denote sample locations in the slumped (non-deformed) rocks. (b–d) Representative thermal demagnetization plots of samples of the Ediacaran Basu Formation from slump-2 (a–b) and non-deformed rocks nearby (c) in stratigraphic coordinates (some samples from non-deformed rocks fall outside the picture). Other notation as in Figs. 2 and 4b–d. (e–g) Stereoplots of high-temperature component, HTC, in the samples from the slump (circles) and non-deformed rocks (inverted triangles) in situ (d), after tilt correction (e), and at optimal unfolding of 55% (f). Other notation as in Figs. 3 and 4e–f. (g) Plot of concentration parameter k versus degree of unfolding for the slump samples only. Solid vertical line denotes 95% confidence level.

symmetric with statistically insignificant and spuriously oriented elongation that, by itself, is evidence against strong shallowing. The features predicted by the TK model are absent as well. For f = 0.9, the elongation slightly increases but remains insignificant; in contrast, ΔGC decreases sharply to ~10° and becomes nearly vertical. The deviation from the circularity is barely discernible (Fig. 6b, Table 4). After the next step (f = 0.8; Fig. 6c), the elongation becomes both visible and statistically significant, while ΔGC becomes negligible; elongation becomes similar to the

Table 3
Paleomagnetic data on two slumps and adjacent sites from the Basu Fm. at locality KK.

Data	n	In situ				Tilt-corrected			
		D°	I°	k	α_{95}°	D°	I°	k	α_{95}°
Slump1	20/20	57.5	−71.9	5.4	15.5	75.7	−52.4	19.1	7.7
C100	7/7	60.1	−33.7	85.0	6.6	65.5	−30.8	184.2	4.5
Slump2	22/15	135.8	−63.1	27.2	7.5	126.9	−43.3	39.4	6.2
55%	22/15					129.6	−53.0	71.5	4.6
C107	8/8	48.2	−50.8	24.0	11.5	63.3	−38.7	25.0	11.3

Notation as in Tables 1 and 2.

TK model predictions. The situation becomes even clearer for f = 0.7 (Fig. 6d, Table 4), with E exceeding the prediction of the TK model. Hence we found no indication of strong inclination shallowing in the Basu data although it remains possible that something on the order of 10% or less shallowing may have occurred.

5. Coherence of the South Urals and Cratonic Baltica

Can we extrapolate the paleomagnetic data from the western Urals to Baltica? The answer to this question requires evidence that the sampled region was not a far-traveled terrane that had docked to Baltica during the Paleozoic. We noted earlier that the Neoproterozoic sequences (~900–542 Ma) are reliably traced from the fold belt to the Ural Foredeep and further to the eastern parts of Baltica; this correlation is supported by a series of seismic profiles (Stratotype of the Riphean: Stratigraphy, Geochronology, 1983; Puchkov et al., 2001; Maslov, 2004; Kuznetsov et al., 2010). Despite the gaps in geologic record, no angular unconformities are found between Ediacaran through Paleozoic sedimentary rocks until the mid-Permian in the westernmost units of the South Urals (Puchkov, 2003). Thus, there are no traces of any collisional events from the late Neoproterozoic until the Permian. Taking these two lines of evidence together we are confident that the western tectonic units of the Urals are a part of the cratonic Baltica margin, deformed in Permian time (Puchkov, 2003; Maslov, 2004; Bogdanova et al., 2008; Levashova et al., 2013).

While the study area can be reliably tied to cratonic Baltica, it does not preclude rotation of these units with respect to the craton during the Permian orogenesis. In an effort to evaluate this possibility, Levashova et al. (2013) studied Paleozoic and Neoproterozoic rocks at several localities and have isolated a synfolding component with SW and up directions. The mean direction of this overprint was found to agree within few degrees with the reference directions recalculated from the apparent polar wander path of Baltica for the interval from 300 to 270 Ma. As major folding in the studied westernmost part of the South Urals took place in Kungurian time (Puchkov, 2003), the observed agreement speaks against relative rotation between this part of the Urals and cratonic Baltica (Levashova et al., 2013). Thus, both geologic and paleomagnetic data do not reveal significant relative motions between the study area and craton, and paleomagnetic data from these western Uralian units can be used to constrain the paleogeography of Baltica during the Ediacaran interval.

Table 4
Results of distribution-shape analysis for 195 HTC sample directions.

f	D°	I°	k	α_{95}°	ΔGC°	E	E_{pr}
1.0	55.4	−36.4	17.0	2.5	40.5	1.14	2.1
0.9	55.4	−40.3	16.2	2.6	9.5	1.22	2.0
0.8	55.4	−45.2	15.2	2.7	3.7	1.70	1.9
0.7	55.4	−51.3	14.1	2.8	2.8	2.46	1.7

Comments. f, flattening. ΔGC, angular deviation of the great circle fitted to the data from the stereonet center. E, observed elongation value. E_{pr}, predicted elongation value (interpolated from Tauxe and Kent (2004)). 95% critical value of E is ~1.3. Other notation as in Table 1.

6. Interpretation and discussion

The aforementioned paleomagnetic and geological data allow us to conclude that: 1) the rocks of the Basu Formation were deposited between 570 and 560 Ma; 2) the high temperature component of magnetization in these rocks is of primary origin; 3) inclination shallowing is negligible; and 4) the Basu Formation pole can be extrapolated to Baltica. Thus, we can include this result in the list of Ediacaran paleomagnetic poles for Baltica (Table 5).

Cambrian–Late Precambrian — APWPs for Laurentia and Baltica are a matter of considerable debate because the existing set of paleomagnetic data for this time interval is highly controversial (Meert, 2014). Thus, before speculating on Laurentia and Baltica relationships and the possible timing of the Iapetus opening, one must review the Late Precambrian–Cambrian paleomagnetic data for these two continents.

6.1. Early Ordovician–Ediacaran paleomagnetic data from Baltica

The well-defined Early Ordovician (480 Ma) mean pole (Torsvik et al., 2012) forms a useful 'anchor-point' for evaluating plate motion implied by the Ediacaran–Cambrian paleomagnetic data (EO in Table 5). The poles for Baltica for the interval from 615 to >480 Ma are listed in Table 5 and compared with the Baltic APWP in Fig. 7.

A pole on Upper Cambrian (ca. 500 Ma) Andarum shale (AS, Table 5; Torsvik and Rehnström, 2001) is based on eleven samples only. The Narva sediment pole (NS; Table 5) is based on eleven samples of Lower Cambrian fine-grained sediments but is confirmed by the reversal test (Khramov and Iosifidi, 2009). The Early Cambrian (about 535 Ma) Tornetrask/Dividal results are derived from sediments along the Caledonian front (T; Table 5; Torsvik and Rehnström, 2001). The Nekso sandstone pole (NE; Table 5; Lewandowski and Abrahamsen, 2003) is derived from a horst block within the Caledonian deformational region.

Upper Ediacaran sediments outcrop along the southeastern coast of the White Sea; their stratigraphic age is confirmed by the ~555 Ma U–Pb age on zircons from ash beds (Martin et al., 2000; Grazhdankin, 2003). Four consistent poles (Z, VH, AR, WC; Table 5) from a narrow stratigraphic interval (~550–555 Ma) are available from this area (Popov et al., 2002; Iglesia Llanos et al., 2005; Popov et al., 2005).

In Volhynia (southwestern Baltica), the Ediacaran section comprises several hundred meters of thick succession of lava flows and tuffs (known mostly from boreholes) that is overlain by a 200 meter thick sedimentary cover (Velikanov, 1985). Few U–Pb ages on zircons from the volcanic rocks yield a late Ediacaran–Fortunian age of ca. 540–550 Ma (Compston et al., 1995), although older ages of ~580 Ma were inferred from $^{40}Ar/^{39}Ar$ data (Elming et al., 2007). Three teams independently studied paleomagnetism of these volcanics (Iosifidi et al., 2001; Nawrocki et al., 2004; Elming et al., 2007). Sampling was limited to two small quarries with no more than four cooling units in the northern part of Volhynia, and one or two cooling units only were sampled in two small quarries in the south. Elming et al. (2007) note that the "northern" sites (VN; Table 5) indicate a high-paleolatitude position for Baltica, whereas the "southern" sites (VS; Table 5) place central Baltica at a latitude of ~20°, N or S. Iosifidi et al. (2005) studied overlying Ediacaran sediments in the same area and recognized six different remanent directions, some of them bi-polar, in these rocks. Our re-evaluation of these data shows that the distributions of component directions strongly overlap and just two very diffuse clouds can be recognized (not illustrated). Therefore, there is a reason to question the validity of each mean direction reported by Iosifidi et al. (2005); we note, however, that none of their directions infers a high-latitude position for Baltica during the Late Ediacaran–Early Cambrian.

The Zigan pole (550–542 Ma; Z in Table 5; Levashova et al., 2013) was derived from the Zigan Fm. red beds from the westernmost tectonic units of the Ural fold belt located at deformed eastern margin of Baltica. This remanence is likely primary as indicated by a positive reversal test

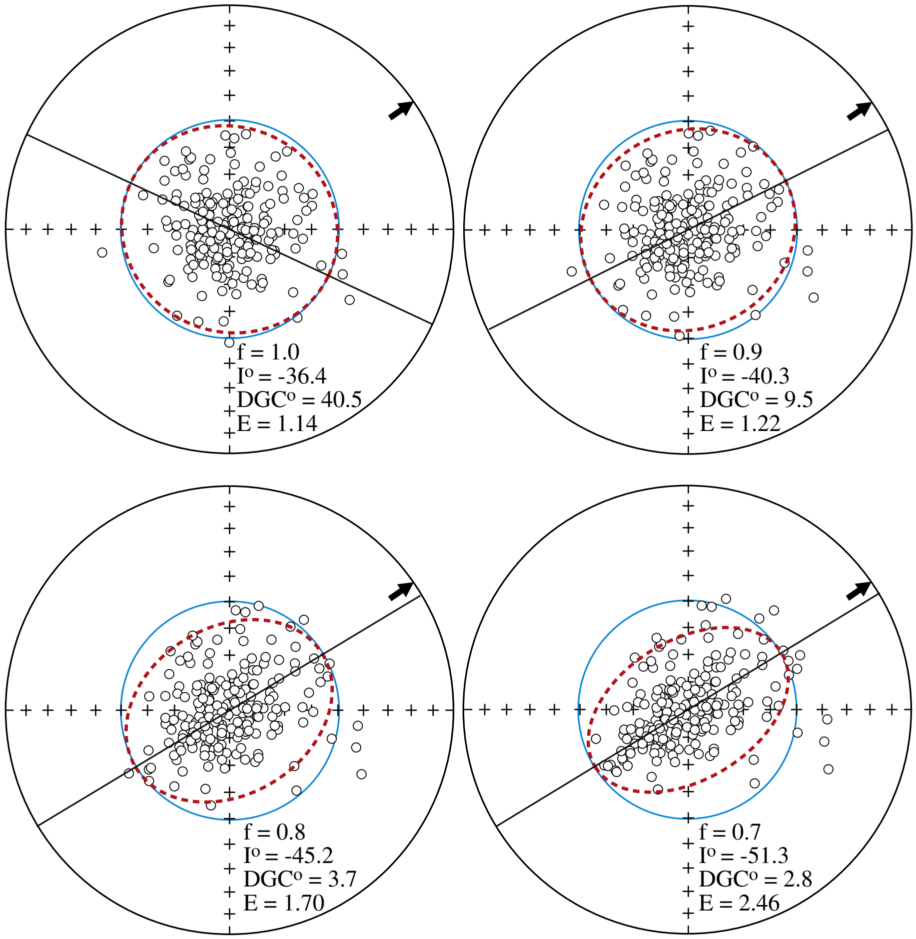

Fig. 6. Stereoplots of HTC sample directions (circles) for different values of shallowing factor (see text for detail) transferred to the projection pole. Thin blue circle is shown for scale. Thick dashed red ellipse drawn according to the elongation parameter E is to highlight the form of the distribution, with its long axis shown as solid black line. Solid arrow denotes mean declination of the HTC.

Table 5
Paleomagnetic poles from Baltica (Late Ediacaran–Early Ordovician).

Key	Rock unit	LLat °N	Llong °E	Age	Pole (north)		A_{95}°
					Lat°	Long°	
EO	480 Ma mean pole			480	−27	239	6.6
NS	Narva Sediments	59	28	500	−22	267	6.0
AS	Andrarum Shale	56	14	500	−52	291	8.5
T	Tornetrask Fm.	68	19	535	−56	295	13.2
NE	Nekso Sandstone	55	15	545	−40	357	5.3
VN	Volhynia North	53	28	540–550	−20	184	3.3
VS	Volhynia South	53	28	540–550	−24	103	3.3
ZI	Zigan Fm.	54	57	542–550	−16	138	3.7
Z	Zolotitsa	65	40	550–555	−32	113	2.1
VH	Verkhotina	65	40	550–555	−32	117	2.0
AR	Arkhangelsk	65	40	550–555	−28	110	3.5
WC	Winter Coast	65	40	550–555	−25	132	2.9
VWZ[a]	VS, Z, VH, AR, WC, ZI			540–555	−27	119	11.4
BA	Basu Fm.	54	57	560–570	2	186	3.8
F	Fen Complex	50	9	583	−57	331	8.8
A1	Alnø steep	62	17	584	−63	281	13.3
A2	Alnø shallow	62	17	584	−4	89	24.4
ED	Egersund Dykes	58	6	616	−31	224	15.7

Comment: References by pole labels: (EO) — Torsvik et al. (2012); (NS) — Khramov and Iosifidi (2009); (AS, T) — Torsvik and Rehnström (2001); (NE) — Lewandowski and Abrahamsen (2003); (VN, VS) — Elming et al. (2007); (ZI) — Levashova et al. (2013); (ZO, VH) — Popov et al. (2005); (AR) — Iglesia LLanos et al. (2005); (WC) — Popov et al. (2002); (BA) — this study; (F) — Meert et al. (1998); (A1, A2) — Meert et al. (2007); (ED) — Walderhaug et al. (2007). Llat, Locality latitude (°N). Llong, Locality longitude (°E). Plat, Paleomagnetic pole latitude (°N if positive). Plong, Paleomagnetic pole longitude (°E). A_{95} (°), radius of confidence circle for paleomagnetic poles (Fisher, 1953). Age, rock age in Ma.
[a] Overall mean of the listed poles.

and regional consistency test. Similar to the Basu data, this result can be extrapolated to cratonic Baltica. The Zigan pole falls into the cluster formed by the White Sea poles and South Volhynia pole (Fig. 7). Good grouping of the data from three remote parts of the craton makes the overall Late Ediacaran mean pole (VWZ, Table 5) a useful “anchor-point” for constructing the pre-Ordovician part of the Baltic APWP.

The Basu pole (575–560 Ma, BA in Table 5) is described in this study. Although the Asha Series is usually described as a conformable pile of five formations this is due primarily to a lack of precise ages and/or diagnostic fossils (Stratotype of the Riphean: Stratigraphy, Geochronology, 1983). Paleomagnetic data are available only from the Basu and Zigan Fms., which are separated by the relatively thin Kuk-Karauk Fm. with reportedly gradual upper and lower boundaries. The large difference between the corresponding poles (Table 5) must also be explained in terms of the available age constraints for the two units.

Paleomagnetic data are available on the Fen Complex in southern Norway (Poorter, 1972; Piper, 1988; Meert et al., 1998) and Alnö Complex in central Sweden (Piper, 1981; Meert et al., 2007). These carbonatite complexes are nearly coeval (~585 Ma), and their corresponding paleomagnetic data can place the study locations in Baltica at intermediate latitudes (Fen complex, F; Table 5), close to the geographic pole (Alnö steep component, A1; Table 5) or in the tropics (Alnö shallow component, A2; Table 5). Meert (2014) showed that the Fen paleomagnetic pole is most likely a remagnetization acquired during the opening of the Oslo Rift (Permo-Triassic) and that the Alno data are of too poor quality to merit further discussion.

The sole Early Ediacaran pole comes from the Egersund dykes in SW Norway (E; Table 5; Walderhaug et al., 2007). This pole is reliably dated

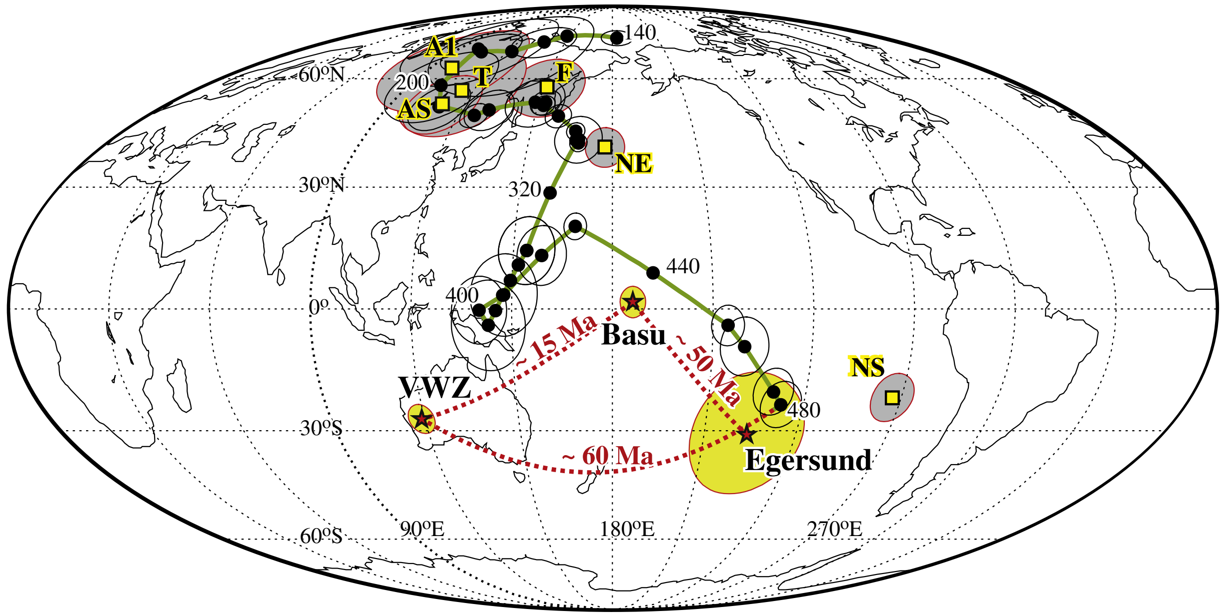

Fig. 7. The APWP's for Baltica for the 140–480 Ma interval (Torsvik et al., 2012) and the selected Cambrian–Ediacaran paleomagnetic poles from Baltica keyed as in Table 5 and the text. Reference data are shown as north poles (solid dots) with associated confidence circles (thin solid lines) connected with thick solid green line; the ages in Ma are shown for some reference poles. The Ediacaran poles that are used for interpretation are shown as stars with yellow-filled confidence circles and connected with thick dashed lines with the age differences between neighboring data; the poles that are discussed but discarded are shown as squares with gray-filled confidence circles.

at 616 ± 3 Ma (zircon U–Pb age) and is confirmed by a positive baked contact test.

Comparison of the Ediacaran–Cambrian and reference data for Baltica shows that the Andarum, Tornetrask, Alno1 and Fen poles fall directly on the Early Mesozoic–Permian segment of the APWP, while the Nekso pole falls within 10° of this overprint direction (Fig. 7). We feel that this similarity to a younger pole along with the lack of evidence for a primary remanence in these rocks, thus strongly undermine the validity of these data. The Egersund dykes pole also falls near the Early Ordovician mean pole for Baltica (within 11°) although the age of its remanence is supported by a baked contact test.

The Narva pole was considered by Khramov and Iosifidi (2009) as representative of a remagnetization at the Cambrian–Ordovician boundary, although it differs by more than 30° from the nearest reference pole. The Narva result is based on limited statistics and thus should not be used as a tie-point in any tectonic analysis. The same arguments pertain to the Volhynia North pole. The WZV appears to be the most trustworthy in the data list analyzed, while the primary origin and reliability of the Basu result have been already argued. Thus, for the Ediacaran–Early Ordovician interval, the paleoposition of Baltica can be ascertained from the four poles only, which are the 480 Ma reference, VWZ, Basu, and the Egersund poles. The resulting very schematic APWP (Fig. 7) infers the following kinematic scenario:

1) Egersund–Basu (616–565 Ma) interval. Baltica moves from high to low latitudes by 45° at velocity of ~0.9°/Ma (9 cm/year) and rotates by ca. 30° CW.
2) Basu–VWZ (565–550 Ma) interval. Baltica moves to a still lower latitude at a velocity of ~0.8°/Ma (8 cm/year) and quickly rotates by ca. 50° CW.
3) VWZ–Early Ordovician (550–480 Ma) interval. Baltica reverses its motion and drifts poleward at a velocity of ~0.7°/Ma (7 cm/year). The sense of rotation is reversed and the craton rotates by ca. 100° CCW.

All inferred motions with poleward velocities between 7 and 9 cm/year are rather fast but similar and even larger velocities are not uncommon.

6.2. Early Cambrian–Ediacaran paleomagnetic data from Laurentia

The Early Ordovician and Middle to Late Cambrian parts of the Laurentia's APWP are based on a sufficient number of mutually consistent paleopoles, and we rely on the existing APWP (Torsvik et al., 2012). As for the Early Cambrian to Ediacaran poles, we mostly follow the choice of McCausland et al. (2007).

Two poles are listed in Table 6 for Early Cambrian time. McCausland et al. (2007) claim that the result on the 532 Ma Mont Rigaud stocks satisfies all quality criteria (Van der Voo, 1990), except for the clearly positive field test. Three poles are tabulated for Late Ediacaran time (Table 6), although none of them provides a well-resolved pole position for Laurentia. The 550 ± 3 Ma Skinner Cove Fm. result (SC; McCausland and Hodych, 1998) is from western Newfoundland, which is allochthonous to Laurentia. This area probably never was far away from the continent margin (Cawood et al., 2001; Hodych et al., 2004) but the lack of relative rotations and, hence, full coherency with Laurentia was not demonstrated. Dual-polarity shallow directions are reported from the carbonate Johnnie Fm. (JR, Van Alstine and Gillett, 1979), but the rock age is poorly constrained. Basing on the assumed age of the overlying rocks, Meert et al. (1994) estimated these carbonates as ca. 555 Ma although more recent estimates constrain the age of the Johnnie to 'younger than 580 Ma' (Kaufman et al., 2007; Trower and Grotzinger, 2010; Petterson et al., 2011). Finally, the 565 Ma Sept Iles intrusion has a shallow 'A' magnetization (SI-A) in the intrusion only and a steep dual-polarity 'B' magnetization (SI-B) present in four mafic dykes and several sites in the intrusion (Tanczyk et al., 1987). These researchers interpreted the 'A' remanence as primary because it has higher coercivity and unblocking temperature; this view is supported by a positive inverse contact test. Collectively, SC, JR and SI-A poles suggest that Laurentia was located at low latitudes in the Late Ediacaran.

For the Early Ediacaran epoch, the 572 ± 5 Ma Catoctin basalts carry three different components of magnetization (Meert et al., 1994). A steep Catoctin 'A' remanence (CT-A) passes the baked contact test and McCausland et al. (2007) suppose it to be of primary origin. However, the pre-folding dual-polarity shallow 'B' remanence (CT-B) is also found in Catoctin basalts and is interpreted as primary in other studies

Table 6
Early Cambrian–Ediacaran paleomagnetic poles from Laurentia.

Key	Rock unit	Llat °N	Llong °E	Age	Pole (north)		A_{95}°	Pos
					Lat°	Long°		
MR	Mont Rigaud	45.4	285.7	532 ± 2	−12	185	4.8	L
SC	Skinner Cove Fm.	49.5	302.0	550 ± 3	16	157	9.1	L
JR	Johnnie Fm. (unrotated)	36.8	244.7	ca. 555	10	122	8.0	L
SI-A	Sept Iles intrusion 'A'	50.2	295.5	564 ± 4	20	141	7.1	L
SI-B	Sept Iles intrusion 'B'	50.2	295.5	564 ± 4	−44	134	9.8	H
CT-A	Catoctin Basalts 'A'	38.5	281.8	572 ± 5	−42	117	17.5	H
CT-B	Catoctin Basalts 'B'	38.5	281.8	572 ± 5	−4	184	10.0	L
CT-C	Catoctin Basalts 'C'[a]	38.5	281.8	572 ± 5	19	134	9.4	L
CC	Callander Complex	46.2	280.6	577 ± 1	−46	121	6.0	H
GD-A	Grenville Dykes 'A'	46.0	282.0	590 ± 2	−3	151	12	L
GD-B	Grenville Dykes 'B'	46.0	282.0	590 ± 2	−60	160	14.0	H
LR	Long Range dykes	53.7	303.1	615 ± 2	−19	175	17.4	L

Comments: References by pole labels: (MR) — McCausland et al. (2007); (SC) — Cawood et al. (2001); (JR) — Meert et al. (1994), but see Hodych et al., and discussion in the text; (SI) — Tanczyk et al. (1987); (CT) — Meert et al. (1994); Aleinikoff et al. (1995); (CC, GD) — Symons and Chiasson (1991); Kamo et al. (1995); (LR) — Kamo et al. (1989) and Kamo and Gower (1994). Pos, inferred position of Laurentia: H, high-latitude; L, low-latitude. Other notation as in Table 5.

[a] Identified as a Middle Paleozoic overprint by Meert et al. (1994).

(Hodych et al., 2004; Murphy et al., 2004). The Catoctin 'C' component (CT-C) was isolated at intermediate temperatures, and Meert et al. (1994) argued that it was the result of Middle Paleozoic overprinting. The 577 ± 1 Ma Callander complex carry a steeply directed dual-polarity remanence (CC) that passes the baked contact test (Symons and Chiasson, 1991; Kamo et al., 1995). The 590 Ma Grenville Dykes steep 'B' remanence (GD-B) was interpreted as primary (Murthy, 1971; Buchan et al., 2004), while the shallow 'A' directions in other Grenville Dykes (Murthy, 1971) do not have supporting field test and are supposed to be of secondary origin.

The first paleomagnetic study from the 615 Ma Long Range dykes (Murthy et al., 1992) was later recalculated by Hodych et al. (2004). This recalculated result (LR) for five out of the six dykes encompasses two polarities, and, despite poor resolution, suggests a low latitude location of Laurentia.

In full accord with earlier papers (e.g., McCausland et al., 2007), our analysis points to existence of two groups of poles: one of them suggests a low-latitude position for Laurentia, while the other group places it in high latitudes (Table 6; Fig. 8a). Four poles inferring a high-latitude position for Laurentia range in age from 590 Ma to 564 Ma and do not overlap its Phanerozoic APWP for any polarity option. In contrast, all low-latitude poles are in good to excellent agreement with the Early-Middle Paleozoic segment of this APWP (Fig. 8a). Moreover, the Laurentian low-latitude poles for the 615–530 Ma window do not outline any clear progression with age; instead, they reveal an erratic pattern with nearly identical start- and end-points (Fig. 8b). One way to explain the above features is to hypothesize several remagnetization events at different parts of east Laurentia, but testing this hypothesis against geological data is out of scope of this paper. An argument against this assumption is the positioning of the Johnnie pole from western Laurentia where no tectonic events are known in the Middle Paleozoic.

The subject of Laurentia's paleolatitude in the Ediacaran remains enigmatic. Until the early 1990's, Laurentia was placed at low latitudes until several studies pointed to a possible high-latitude position for Laurentia (Symons and Chiasson, 1991; Park, 1992; Meert et al., 1994; Park, 1994). A high-latitude position was then generally accepted in the literature until questioned by Pisarevsky et al. (2000); see also comments by Meert and Van der Voo (2001) and reply by Pisarevsky et al. (2001). While not conclusive, the low-latitude position for Laurentia has become 'favored' in more recent literature and an explanation for the high latitude results remains elusive.

6.3. Tectonic implications

Paleogeographic and tectonic reconstructions require reasonably precise constraints on the timing of continental rifting and initiation of ocean spreading, timing of ocean closure and continental collision, and positions of the continents through time. To reconstruct the Laurentia and Baltica relationships and the process of the Iapetus Ocean opening and evolution in the Late Precambrian–Early Paleozoic one needs both paleomagnetic data from the two continents and geological evidence on the process of the Iapetus opening.

The Humber zone of the Appalachian orogen represents the eastern margin of Laurentia and preserves a record of continental margin initiation associated with opening of the Iapetus Ocean (Williams, 1995; Cawood et al., 1996, 2001). This zone consists of crystalline basement of the Grenville province unconformably covered by a sequence containing rift, continental margin, and foreland basin units. Rift sequences contain mafic to felsic volcanic flows and intrusions, while drift sequences are carbonate-dominated. Two pulses of rifting, from ca. 760 to 700 Ma and from ca. 620 to 550 Ma, are recognized along the eastern margin of Laurentia (Aleinikoff et al., 1995; Mitchell et al., 2011; O'Brien and van der Pluijm, 2012). The first pulse is correlated to the opening of the proto-Pacific between the west Laurentia and East Australia–West Antarctica conjugate margins (Powell et al., 1993; Powell, 1995; Wingate and Giddings, 2000). Younger rift-related magmatic activity, widespread in the central to northeastern Appalachians (Aleinikoff et al., 1995), is associated with the opening of the Iapetus Ocean, first between Laurentia and Baltica, and then between Laurentia and elements of west Gondwana.

Geological data indicate that igneous activity at the Laurentian margin continued in a rift setting until ca. 550 Ma (cf. Kumarapeli et al., 1989; Williams, 1995; Cawood et al., 1996; Higgins and van Breemen, 1998). However, McCausland and Hodych (1998) suggested that post-570 Ma magmatism may reflect either igneous activity along the failed Ottawa-Bonnechere rift arm, or passive margin alkalic magmatism. Thus, the initiation of Iapetus spreading started either at about ca. 570 Ma, or at about ca. 550 Ma. A younger limit on the timing of the initiation of seafloor spreading is provided by the age of the earliest drift-related sedimentation, which is probably not older than ca. 525–520 Ma (Cawood et al., 2001).

The Iapetus traces are more limited in Europe, being confined to some rift-related magmatic complexes in Norway (Dahlgren, 1994; Meert et al., 1998), Sweden (Meert et al., 2007) and the British Isles (van Staal et al., 1998) along with rift-related mafic dykes (Bingen et al., 1998).

The paleogeographic reconstructions for Early Ordovician interval that includes the Tremadocian and early Arenigian (beginning at 490 Ma, ending at 471 Ma) seem to be most reliable due to the large number of faunal and paleomagnetic studies that have been undertaken on the rocks of this age. In the Early Ordovician, both "Baltica" and "West Gondwana" arms of the Iapetus Ocean were at their widest (Torsvik and

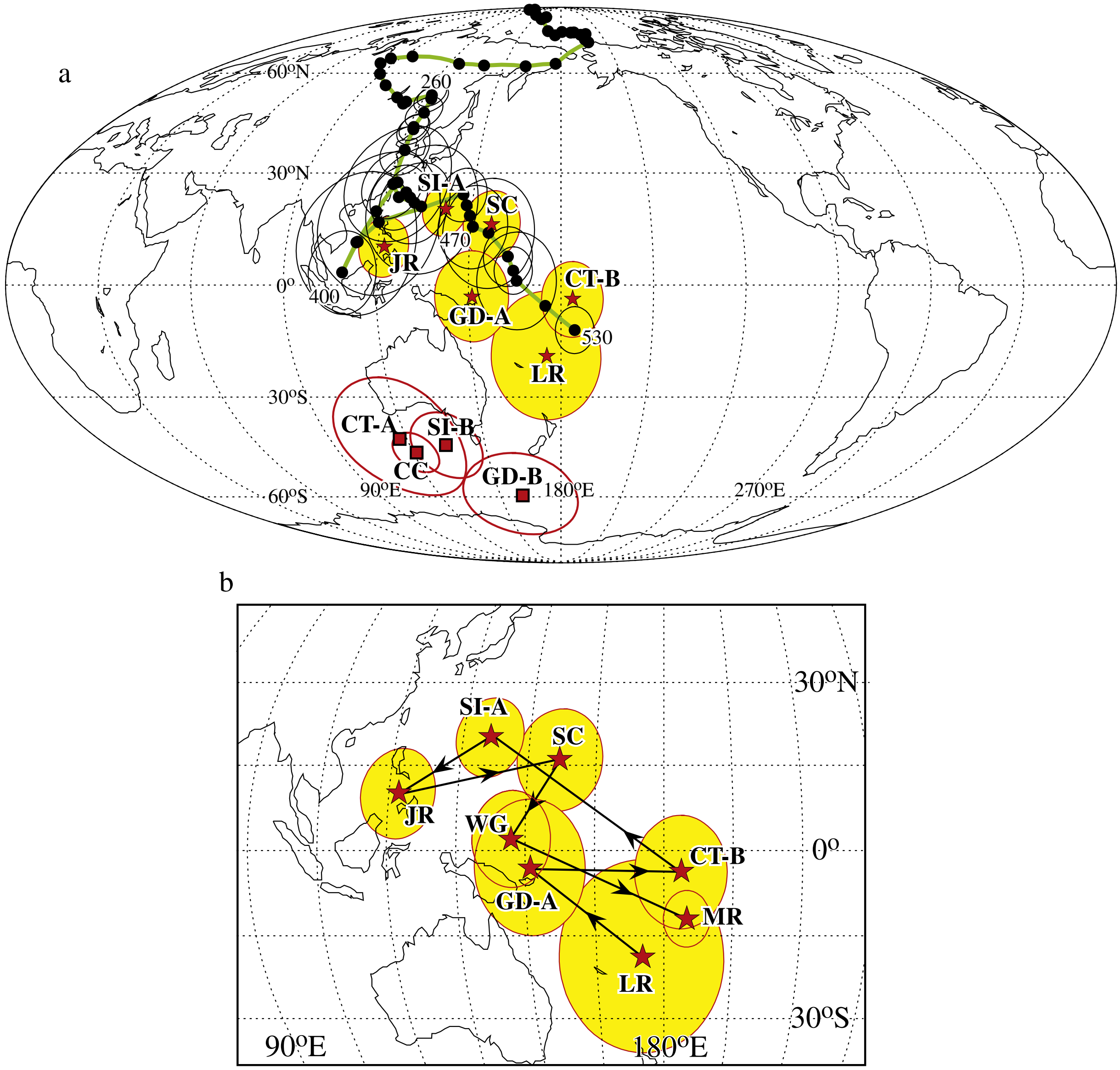

Fig. 8. (a) The Phanerozoic APWPs for Laurentia (Torsvik et al., 2012) and the selected Ediacaran paleomagnetic poles from Laurentia keyed as in Table 6 and the text. Reference data are shown as north poles (solid dots) with associated confidence circles (thin solid lines; not shown for Mesozoic and Cenozoic for clarity) connected with thick solid green line; the ages in Ma are shown for some reference poles. The Ediacaran poles that infer a low-latitude position of Laurentia are shown as stars with yellow-filled confidence circles; the "high-latitude" poles are squares with non-filled confidence circles. (b) The time succession of the Early Cambrian–Ediacaran paleomagnetic poles from Laurentia. Arrow-heads point from older to younger data. Other notation as in Fig. 8a.

Trench, 1991; Cocks and Torsvik, 2002). Hence the early Ordovician reconstructions (Fig. 9a) can be used as a starting point for evaluating the earlier paleogeography.

Gondwana was mostly assembled at around 550–540 Ma (Meert and Van der Voo, 1997; Meert, 2003; Meert and Lieberman, 2008), although the fusion of some cratonic elements (Amazonia, West Africa) with central Gondwana may have occurred during Middle to Late Cambrian times (Tohver et al., 2006). At the time of Iapetus Ocean opening, Gondwana did not exist as a single continent, and thus we will deal only with the Baltica–Laurentia relationships in our reconstructions.

The position of Baltica during the Cambrian is poorly unknown, as there are no unambiguous paleomagnetic data for this time interval. At the end of the Ediacaran (~550 Ma), Baltica's position is defined by the group of paleomagnetic poles (VWZ, Table 5; Fig. 9b). The position of Laurentia at that time is defined only by the 550 $\pm$ 3 Ma Skinner Cove Formation (Table 6). According to the limited data, Laurentia is located at low latitudes at the end of the Ediacaran and the "Baltica" arm of the Iapetus Ocean is already rather wide (Fig. 9b).

For the 575–560 Ma interval, the position of Baltica is defined by the Basu pole (BA in Table 5), and there are three paleomagnetic results from Laurentia (Table 6). The 565 Ma Sept Iles intrusion has a shallow 'A' magnetization and a steep dual-polarity 'B' magnetization (Tanczyk et al., 1987). The 572 $\pm$ 5 Ma Catoctin basalts carry three different components of magnetization (Meert et al., 1994): a steep Catoctin 'A' remanence, a shallow Catoctin 'B' remanence and a Catoctin 'C' component that was isolated at intermediate temperatures and is supposed to be a Middle Paleozoic overprint. The 577 $\pm$ 1 Ma Callander complex carries a steeply directed dual-polarity remanence (Symons and Chiasson, 1991; Kamo et al., 1995).

The Sept Iles 'A' result and the Catoctin 'B' remanence suggest the low latitude paleoposition of Laurentia 575–565 Ma ago as does the imprecisely dated Johnnie Formation, while the Sept Iles 'B', Catoctin 'A' and Callander complex remanences imply a high latitude position for

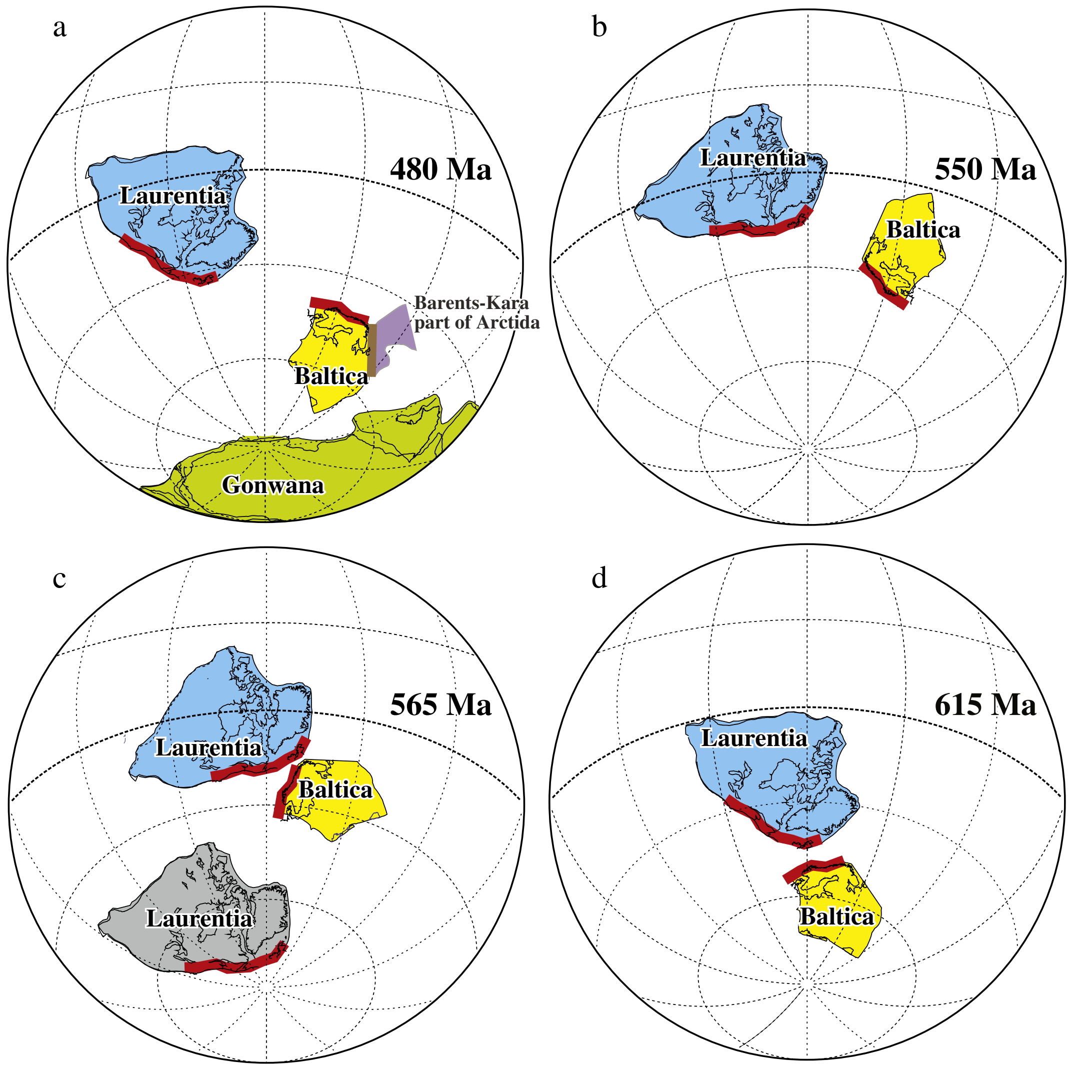

Fig. 9. The Baltica–Laurentia relationship at different times according to paleomagnetic poles listed in Tables 5 and 6. (a) "Standard" reconstruction for 480 Ma using mean poles for all continents from Torsvik et al. (2012); (b) reconstruction for 550 Ma using the VWZ pole for Baltica and the Skinner Cove pole for Laurentia; (c) reconstruction for 565 Ma using the Basu pole for Baltica and the Sept Iles A and B poles for Laurentia; (d) reconstruction for 615 Ma using the Egersund Dykes pole for Baltica and the Long Range Dykes pole for Laurentia. Longitudinal separation of continents is arbitrary. Baltica is yellow, low-latitude Laurentia is blue, and high-latitude Laurentia is gray. Red bands denote the margins of the late Neoproterozoic Iapetus Ocean.

Laurentia at that time. If the low-latitude Sept Iles 'A' and Catoctin 'B' poles are used, Baltica and Laurentia can be positioned close to each other and suggest a relatively narrow Iapetus Ocean. If we suppose the Sept Iles 'B', Catoctin 'A' and Callander complex remanences to be of primary origin, Laurentia must have been far to the south of Baltica with a wide Iapetus Ocean (Fig. 9c).

There are no paleomagnetic data for Baltica between 575 and 560 Ma Basu and the 616 ± 3 Ma Egersund dykes poles (Table 5). The oldest Early Ediacaran result — the 615 Ma Long Range dykes pole suggests a low latitude position for Laurentia, but is based on only five dykes. According to geological data, the Iapetus Ocean had not yet opened at 615 Ma. Paleomagnetic data from the nearly coeval Long Range Dykes and Egersund Dykes poles are consistent with a relatively tight fit between the two continents (Fig. 9d) given the errors in age and position. A strange dichotomy exists between the geological and paleomagnetic data. The "low-latitude Laurentia" scenario is in agreement with the geological data, but poles from Laurentia and Baltica used to constrain the paleogeography are similar to younger poles and thus potentially represent remagnetizations. In contrast, the "high latitude scenario" looks less suspicious from a paleomagnetic perspective (i.e. the poles are unique for the last 600 Ma), but require a wide Iapetus Ocean in direct contrast to the available geological data.

7. Conclusions

A paleomagnetic study of gray and maroon sandstone and siltstone of the Basu Formation (Ediacaran-age) from the eastern deformed margin of Baltica was carried out at several localities spread over 150 km. The age of the Basu Formation is constrained to the 570–560 Ma interval by correlation, fossils and isotopic ages of overlying and underlying units. A dual-polarity magnetization was isolated in about two-thirds of a large collection. The HTC is considered primary on the basis of positive reversal, fold and slump tests. A schematic APWP for Baltica reveals motion of this craton with velocities of 7 to 9 cm/year for the 480–615 Ma interval. An attempt to reconstruct the early stages of the Iapetus Ocean between Baltica and Laurentia is problematic. As is well known, late Cryogenian and Ediacaran poles for Laurentia form two distinct groups (a high- and a low-latitude ones) that are difficult to reconcile.

Solutions to this conundrum have been proposed (Abrajevitch and Van der Voo, 2010; Mitchell et al., 2011). Mitchell et al. (2011) propose that the swings from low (615 Ma) to high (580 Ma) back to low (550 Ma) latitudes of Laurentia are the result of true polar wander. Abrajevitch and Van der Voo (2010) argue that the Earth's magnetic field exhibited a strange geometry wherein a long-standing equatorial dipole field alternated with a geocentric axial dipole field to produce the apparent high-low latitude transitions. In our opinion, neither option is wholly satisfying. As noted by Meert (2014), the equatorial dipole argument is a global phenomenon that should be reflected in all paleomagnetic data. In the case of Baltica, a review of existing data (repeated above) along with our new result show no swings between high and low latitude results. The true polar wander hypothesis remains possible, but requires additional data from all continents.

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References

Abrajevitch, A., Van der Voo, R., 2010. Incompatible Ediacaran paleomagnetic directions suggest an equatorial geomagnetic dipole hypothesis. Earth and Planetary Science Letters 293, 164–170.

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., Burton, W.C., 1995. U–Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, central and southern Appalachians: evidence for two phases of Iapetian rifting. American Journal of Science 295, 428–454.

Bazhenov, M.L., 1981. Inclination shallowing in Paleogene sandstones of the South Darvaz Range. Doklady Akademii Nauk SSSR 260, 1336–1339 (in Russian).

Bekker, Y.R., 1988. Precambrian Molasses. Nedra, Leningrad (289 pp. (in Russian)).

Bekker, Y.R., 1992. The oldest Ediacaran biota of the Urals. Izvestiya of the Academy of Sciences of the USSR, Geological Series 6, 16–24 (in Russian).

Bekker, Y.R., 1996. The discovery of Ediacaran Fauna in the uppermost Vendian of the South Urals. Regional Geology and Metallogeny, No. 5. VSEGEI, Leningrad pp. 111–131 (in Russian).

Bingen, B., Demaiffe, D., van Breemen, O., 1998. The 616 Ma old Egersund basaltic dike swarm, SW Norway, and late Neoproterozoic opening of Iapetus ocean. The Journal of Geology 106, 565–574.

Bogdanova, S.V., Bingen, B., Gorbatschev, R., Kheraskova, T.N., Kozlov, V.I., Puchkov, V.N., Volozh, Yu.A., 2008. The East European Craton (Baltica) before and during the assembly of Rodinia. Precambrian Research 160, 23–45.

Buchan, K.L., Ernst, R.E., Kumarapeli, P.S., 2004. Paleomagnetism of the Grenville diabase dyke swarm and implications for the mid Vendian paleolatitude of Laurentia. EOS. Transactions of the American Geophysical Union 85 (17) (Abstract GP24A-02, JA166).

Cawood, P.A., van Gool, J.A.M., Dunning, G.R., 1996. Geological development of eastern Humber and western Dunnage zones: Corner Brook — Glover Island region, Newfoundland. Canadian Journal of Earth Sciences 33, 182–198.

Cawood, P.A., McCausland, P.J.A., Dunning, G.R., 2001. Opening Iapetus: constraints from the Laurentian margin in Newfoundland. Geological Society of America Bulletin 113, 443–453.

Cocks, L.R.M., Torsvik, T.H., 2002. Earth geography from 500 to 400 million years ago: a faunal and paleomagnetic review. Journal of the Geological Society, London 159, 631–644.

Cogné, J.P., 2003. PaleoMac: a Macintosh application for treating paleomagnetic data and making plate reconstructions. Geochemistry, Geophysics, Geosystems 4 (1), 1007. http://dx.doi.org/10.1029/2001GC000227.

Compston, W., Sambridge, M.S., Reinefrank, R.F., Moczydlowska, M., Vidal, G., Claesson, S., 1995. Numerical ages, volcanic rocks and the earliest faunal zone within the Late Precambrian of east Poland. Journal of the Geological Society, London 152, 599–611.

Dahlgren, S., 1994. Late Proterozoic and Carboniferous ultramafic magmatism — from the Fen Carbonatite Complex, S. Norway. Lithos 31, 141–154.

Elming, S.-A., Kravchenko, S., Layer, P., Rusakov, O., Glevasskaya, A., Mikhailova, N., Bachtadse, V., 2007. Palaeomagnetism and $^{40}Ar/^{39}Ar$ age determinations of the Ediacaran traps from the southwestern margin of the East European Craton, Ukraine: relevance to the Rodinia break-up. Journal of the Geological Society, London 164, 969–982.

Evans, D.A., 1998. True polar wander, a supercontinental legacy. Earth and Planetary Science Letters 157, 1–8.

Fisher, R.A., 1953. Dispersion on a sphere. Proceedings of Royal Astronomical Society London, Series A 217, 295–305.

Golovanova, I.V., Danukalov, K.N., Kozlov, V.I., Puchkov, V.N., Pavlov, V.E., Gallet, Y., Levashova, N.M., Sirota, G.S., Khairullin, R.R., Bazhenov, M.L., 2011. Paleomagnetism of the Upper Vendian Basu Formation of the Bashkirian Meganticlinorium Revisited. Physics of the Solid Earth 47, 623–635.

Grazhdankin, D.V., 2003. The composition and depositional environment of the Vendian complex in the Southeastern White Sea Region. Stratigraphy and Geological Correlation 11 (4), 3–34.

Grazhdankin, D.V., Marusin, V.V., Meert, J., Krupenin, M.T., Maslov, A.V., 2011. Kotlin regional stage in the South Urals. Doklady Earth Sciences 440, 1222–1226.

Higgins, M.D., van Breemen, O., 1998. The age of the Sept Iles layered mafic intrusion, Canada: implications for the Late Neoproterozoic/Cambrian history of southeastern Canada. Journal of Geology 106, 421–431.

Hodych, J.P., Cox, R.A., Kosler, J., 2004. An equatorial Laurentia at 550 Ma confirmed by Grenvillian inherited zircons dated by LAM ICP-MS in the Skinner Cove volcanics of western Newfoundland: implications for inertial interchange true polar wander. Precambrian Research 129, 93–113.

Iglesia Llanos, M.P., Tait, J.A., Popov, V., Abalmasova, 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 240, 732–747.

Iosifidi, A., Bachtadse, V., Khramov, A., Kuznetsova, A., 2001. Paleomagnetic data for Vendian basalts from Ukraine. 3rd International Conference on Problems of Geocosmos, Abstracts Volume, St. Petersburg, pp. 74–75.

Iosifidi, A.G., Khramov, A.N., Bachtadse, V., 2005. Multicomponent magnetization of Vendian sedimentary rocks in Podolia, Ukraine. Russian Journal of Earth Sciences 7 (1), 1–14.

Iosifidi, A.G., Mikhailova, V.A., Sal'naya, N.V., Khramov, A.N., 2012. Paleomagnetism of sedimentary rocks of the Asha series, the western slope of the South Ural: new results, Oil and Gas Geology. Theory and Practice 7 (4) (http://www.ngtp.ru/rub/2/57_2012.pdf (in Russian)).

Ivanushkin, A.G., Bogoyavlenskaya, O.V., Zenkova, G.G., Breivel, I.A., Kurik, E.Y., 2009. Devonian deposits of western slope of the Urals. Lithosphere 1, 3–22 (in Russian).

Johnson, C.L., Constable, C.G., Tauxe, L., Barendregt, R.W., Brown, L.L., Coe, R.S., Layer, P.W., Mejia, V., Opdyke, N.D., Singer, B.S., Staudigel, H., Stone, D.B., 2008. Recent investigations of the 0- to 5-Ma geomagnetic field recorded by lava flows. Geochemistry, Geophysics, Geosystems 9, Q04032. http://dx.doi.org/10.1029/2007GC001696.

Kamo, S.L., Gower, C.F., 1994. U–Pb baddeleyite dating clarifies age of characteristic paleomagnetic remanence of Long-Range dykes, southeastern Labrador. Atlantic Geology 30, 259–262.

Kamo, S.L., Gower, C.F., Krogh, T.E., 1989. Birthdate for the Iapetus Ocean — a precise U–Pb zircon and baddeleyite age for the Long-Range dykes, southeastern Labrador. Geology 17, 602–605.

Kamo, S.L., Krogh, T.E., Kumarapeli, P.S., 1995. Age of the Grenville dyke swarm, Ontario-Quebec — implications for the timing of Iapetan rifting. Canadian Journal of Earth Sciences 32, 273–280.

Kaufman, A.J., Corsetti, F.A., Varni, M.A., 2007. The effect of rising atmospheric oxygen on carbon and sulfur isotope anomalies in the Neoproterozoic Johnnie Formation, Death Valley, USA. Chemical Geology 237, 47–63.

Khramov, A.N., Iosifidi, A.G., 2009. Paleomagnetism of the Lower Ordovician and Cambrian sedimentary rocks in the section of the Narva River right bank, for the construction of the Baltica kinematic model in the early Paleozoic. Izvestiya, Physics of the Solid Earth 45, 465–481.

King, R.F., 1955. Remanent magnetism of artificially deposited sediments. Monthly Notices of the Royal Astronomical Society, Geophysical Supplement 7, 115–134.

Kirschvink, J.L., 1980. The least-square line and plane and the analysis of palaeomagnetic data. Geophysical Journal of the Royal Astronomical Society 62, 699–718.

Kirschvink, J.L., Ripperdan, R.L., Evans, D.A., 1997. Evidence for a large-scale reorganization of Early Cambrian continental masses by inertial interchange true polar wander. Science 277, 541–545.

Komissarova, R.A., 1963. Paleomagnetic studies of the Asha series from the western slope of the South Urals. Paleomagnetic Stratigraphic Studies. VNIGRI Reports, Leningrad, 204, pp. 69–82 (in Russian).

Komissarova, R.A., 1970. The studies of ancient remanence of some sedimentary rocks in the South Ural and the problem of secondary remagnetization. (PhD thesis), IFZ, Moscow (140 pp. (in Russian)).

Kozlov, V.I., 1982. Upper Riphean and Vendian of the South Urals. Nauka, Moscow (128 pp. (in Russian)).

Kozlov, V.I., (Ed.), 2002. Geological Map of the Russian Federation and Adjacent Territory of the Republic of Kazakhstan. Scale: 1:1 000000 (a New Series). Sheet N-40(41)-Ufa). St. Petersburg: VSEGEI.

Kumarapeli, P.S., Dunnning, G.R., Pintson, H., Shaver, J., 1989. Geochemistry and U–Pb zircon age of comenditic metafelsites of the Tibbit Hill Formation, Quebec Appalachians. Canadian Journal of Earth Sciences 26, 1374–1383.

Kuznetsov, N.B., Natapov, L.M., Belousova, E.A., Reilly, S.Y.O', 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 17, 583–601.

Kuznetsov, N.B., Romanyuk, T.V., Shatsillo, A.V., Golovanova, I.V., Danukalov, K.N., 2012a. The first results of the bulk U/Pb-dating of detrital zircons (LA-ICP-MS) from Asha

Formation, the Southern Urals — the stratigraphic, paleogeographic and paleotectonic aspects. Doklady Earth Sciences 447, 1240–1246.
Kuznetsov, N.B., Romanyuk, T.V., Shatsillo, A.V., Orlov, S.Y., Golovanova, I.V., Danukalov, K.N., Ipatieva, I.S., 2012b. The Age of the detrital zircons from Asha Group, the Southern Urals — verification of idea about the spatial conjugation of Baltica and Australia within the Rodinia Supercontinent (a positive test of the "Australia Upside Down conception"). Lithosphera 4, 59–77 (in Russian).
Kuznetsov, N.B., Meert, J.G., Romanyuk, T.V., 2013. Ages of detrital zircons (U/Pb, La-ICP-MS) from the Latest Neoproterozoic — Middle Cambrian(?) Asha Group and Early Devonian Takaty Formation, the South-Western Urals: a test of an Australia–Baltica connection within Rodinia. Precambrian Research. http://dx.doi.org/10.1016/j.precamres.2013.09.011.
Levashova, N.M., Bazhenov, M.L., Joseph, G., Meert, J.G., Kuznetsov, N.B., Golovanova, I.V., Danukalov, K.N., Fedorova, N.M., 2013. Paleogeography of Baltica in the Ediacaran: paleomagnetic and geochronological data from the clastic Zigan Formation, South Urals. Precambrian Research 236, 16–30.
Lewandowski, M., 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 108. http://dx.doi.org/10.1029/2002JB002281.
Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M.A., Kirschvink, J.L., 2000. Age of Neoproterozoic bilatarian body and trace fossils, White Sea, Russia: Implications for metazoan evolution. Science 288, 841–845.
Maslov, A.V., 2004. Riphean and Vendian sedimentary sequences of the Timanides and Uralides, the eastern periphery of the East European Craton. In: Gee, D.G., Pease, V. (Eds.), The Neoproterozoic Timanides Orogen of Eastern Baltica. Geological Society of London Memoirs, 30, pp. 19–35.
Maslov, A.V., Meert, J., Levashova, N.M., Ronkin, Yu.L., Grazhdankin, D.V., Kuznetsov, N.B., Krupenin, M.T., Federova, N.M., Ipat'eva, I.S., 2013. New constraints for the age of Vendian glacial deposits. Doklady Earth Sciences 449, 303–308.
McCausland, P.J.A., Hodych, J.P., 1998. Palaeomagnetism of the 550 Ma Skinner Cove volcanics of western Newfoundland and opening of the Iapetus Ocean. Earth and Planetary Science Letters 163, 15–29.
McCausland, P.J.A., Van der Voo, R., Hall, C.M., 2007. Circum-Iapetus paleogeography of the Precambrian–Cambrian transition with a new paleomagnetic constraint from Laurentia. Precambrian Research 156, 125–152.
McElhinny, M.W., 1964. Statistical significance of the fold test in palaeomagnetism. Geophysical Journal of Royal Astronomical Society 8, 338–340.
McFadden, P.L., McElhinny, M.W., 1990. Classification of the reversal test in paleomagnetism. Geophysical Journal International 103, 725–729.
Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362, 1–40.
Meert, J.G., 2014. Ediacaran–Early Ordovician paleomagnetism of Baltica: a review. Gondwana Research 25, 159–169.
Meert, J.G., Tamrat, E., 2004. A mechanism for explaining rapid continental motion in the Late Neoproterozoic. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Cantuneanu, O. (Eds.), The Precambrian Earth: Tempos and Events. Developments in Precambrian Geology, 12. Elsevier, Amsterdam, pp. 255–267.
Meert, J.G., Lieberman, B.S., 2008. The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran-Cambrian radiation. Gondwana Research 14, 5–21.
Meert, J.G., Van der Voo, R., 1997. The assembly of Gondwana 800–550 Ma. Journal of Geodynamics 23, 223–235.
Meert, J.G., Van der Voo, R., 2001. Comment on "New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian" by S. A. Pisarevsky, R. A. Komissarova and A. N. Khramov. Geophysical Journal International 146, 867–870.
Meert, J.G., Van der Voo, R., Powell, C.M., Li, Z., McElhinny, M.W., Symons, D.T.A., 1993. A plate-tectonic speed limit. Nature 363, 216–217.
Meert, J.G., Van der Voo, R., Payne, T., 1994. Paleomagnetism of the Catoctin volcanic province: a new Vendian–Cambrian apparent polar wander path for North America. Journal of Geophysical Research 99 (B3), 4625–4641.
Meert, J.G., Torsvik, T.H., Eide, E.A., Dahlgren, S., 1998. Tectonic significance of the Fen Province, S. Norway: constraints from geochronology and paleomagnetism. Journal of Geology 106, 553–564.
Meert, J.G., Walderhaug, H.J., Torsvik, T.H., Hendriks, B.W.H., 2007. Age and paleomagnetic signature of the Alnø carbonatite complex (NE Sweden): additional controversy for the Neoproterozoic paleoposition of Baltica. Precambrian Research 154 (3–4), 159–174.
Mitchell, R.M., Kilian, T.M., Raub, T.D., Evans, D.A.D., Bleeker, W., Maloof, A.C., 2011. Sutton hotpsot: resolving Ediacaran–Cambrian tectonics and true polar wander for Laurentia. American Journal of Science 311, 651–663.
Murphy, J.B., Pisarevsky, S.A., Nance, R.D., Keppie, J.D., 2004. Neoproterozoic–Early Paleozoic evolution of peri-Gondwanan terranes: implications for Laurentia–Gondwana connections. International Journal of Earth Sciences 93, 659–682.
Murthy, G.S., 1971. The paleomagnetism of diabase dykes from the Grenville Province. Canadian Journal of Earth Sciences 8, 802–812.
Murthy, G.S., Gower, C.F., Tubrett, M., Patzold, R., 1992. Paleomagnetism of Eocambrian Long Range dykes and Double Mer Formation from Labrador, Canada. Canadian Journal of Earth Sciences 29, 1224–1234.
Nawrocki, J., Boguckij, A., Katinas, V., 2004. New Late Vendian palaeogeography of Baltica and the TESZ. Geological Quarterly 48 (4), 309–316.
O'Brien, T.M., van der Pluijm, B.A., 2012. Timing of Iapetus Ocean rifting from Ar geochronology of pseudotachylytes in the St. Lawrence Rift System of southern Quebec. Geology 40, 443–446.
Park, J.K., 1992. Did Laurentia pass over the south pole during earliest Cambrian time? Geological Survey of Canada Paper 92-1E, pp. 11–22.
Park, J.K., 1994. Paleomagnetic constraints on the position of Laurentia from middle Neoproterozoic to early Cambrian times. Precambrian Research 69, 95–112.
Petterson, R.J., Prave, A.R., Wernicke, B.P., Fallick, A.E., 2011. The Neoproterozoic Noonday Formation, Death Valley region, California. Bulletin of the Geological Society of America. http://dx.doi.org/10.1130/B30281.1.
Piper, J.D.A., 1981. Magnetic properties of the Alnøn complex. Geologiska Föreningen i Stockholm Förhandlingar 103 (1), 9–15.
Piper, J.D.A., 1988. Paleomagnetism of (late Vendian–earliest Cambrian) minor alkaline intrusions, Fen Complex, southeast Norway. Earth and Planetary Science Letters 90, 422–430.
Pisarevsky, S.A., Komissarova, R.A., Khramov, A.N., 1999. A multicomponent magnetization of the Vendian red sediments from Southern Urals and the palaeoposition of the Baltica. Aarhus Geoscience 8, 95–98.
Pisarevsky, S.A., Komissarova, R.A., Khramov, A.N., 2000. New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian. Geophysical Journal International 140 (3), 598–610.
Pisarevsky, S.A., Komissarova, R.A., Khramov, A.N., 2001. Reply to comment by J. G. Meert and R. Van der Voo on "New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian". Geophysical Journal International 146, 871–873.
Pisarevsky, S.A., Murphy, J.B., Cawood, P.A., Collins, A.S., 2008. Late Neoproterozoic and Early Cambrian palaeogeography: models and problems. In: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., de Wit, M.J. (Eds.), West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. Geological Society, Special Publications, 294, pp. 9–31.
Poorter, R.P.E., 1972. Preliminary paleomagnetic results from the Fen carbonatite complex, S. Norway. Earth and Planetary Science Letters 17, 194–198.
Popov, V., Iosifidi, A., Khramov, A., Tait, J., 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 107. http://dx.doi.org/10.1029/2001JB001607.
Popov, V.V., Khramov, A.N., 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 7 (2), 1–29.
Powell, C.M., 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents?: Comment. Geology 23, 1053–1054.
Powell, C.M., Li, Z.X., McElhinny, M.W., Meert, J.G., Park, J.K., 1993. Palaeomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana. Geology 21, 889–892.
Puchkov, V.N., 2003. The Uralides and Timanides: their structural relationship and position in the geologic history of the Ural–Mongolian fold belt. Russian Geology and Geophysics 44 (1–2), 28–39.
Puchkov, V.N., Svetlakova, A.N., Razuvaev, V.I., 2001. Geologic interpretation of the URALSEIS seismic profile (western domain). In: Morozov, A.F. (Ed.), Deep Structure and Geodynamics of the South Urals (URALSEIS Project). GERS Publishers, Tver, pp. 148–154 (in Russian).
Ronkin, Y., Grazhdankin, D.V., Maslov, A.V., Mizens, G.A., Matukov, D.I., Krupenin, M.T., Petrov, G.A., Lepikhina, O.P., Kornilova, A.Y., 2006. U–Pb (SHRIMP II) age of zircons from ash beds of the Chernokamen Formation, Vendian Sylvitsa Group (Central Urals). Doklady Earth Sciences 411, 1341–1345.
Stratotype of the Riphean: Stratigraphy, Geochronology, 1983. B.M. Keller and N.M. Chumakov, eds., Nauka, Moscow, 184 pp. (in Russian).
Sun, W.W., Kodama, K.P., 1992. Magnetic anisotropy, scanning electron microscopy, and x ray pole figure goniometry study of inclination shallowing in compacting clay-rich sediment. Journal of Geophysical Research 97, 19,599–19,616.
Symons, D.T.A., Chiasson, A.D., 1991. Paleomagnetism of the Callander complex and the Cambrian apparent polar wander path for North America. Canadian Journal of Earth Sciences 28, 355–363.
Tan, X., Kodama, K.P., 2002. Magnetic anisotropy and paleomagnetic inclination shallowing in red beds: evidence from the Mississippian Mauch Chank Formation, Pennsylvania. Journal of Geophysical Research 107, 2311. http://dx.doi.org/10.1029/2001JB001636.
Tanczyk, E.I., Lapointe, P., Morris, W.A., Schmidt, P.W., 1987. A paleomagnetic study of the layered mafic intrusion at Sept-Iles, Quebec. Canadian Journal of Earth Sciences 24, 1431–1438.
Tauxe, L., 2005. Inclination flattening and the geocentric axial dipole hypothesis. Earth and Planetary Science Letters 233, 247–261.
Tauxe, L., Kent, D.V., 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: was the ancient magnetic field dipolar? In: Channell, J.E.T., Kent, D.V., Lowrie, W., Meert, J.G. (Eds.), Timescales of the Paleomagnetic Field. AGU Geophys. Monogr., 135, pp. 101–116.
Tauxe, L., Kylstra, N., Constable, C., 1991. Bootstrap statistics for paleomagnetic data. Journal of Geophysical Research 96, 11723–11740.
Tohver, E., D'Agrella-Filho, M.S., Trindade, R.I.F., 2006. Paleomagnetic record of Africa and South America for the 1200–500 Ma interval, and evaluation of Rodinia and Gondwana assemblies. Precambrian Research 147, 193–222.
Torsvik, T.H., Rehnström, E.F., 2001. Cambrian palaeomagnetic data from Baltica: implications for true polar wander and Cambrian palaeogeography. Journal of the Geological Society, London 158, 321–329.
Torsvik, T.H., Trench, A., 1991. Ordovician magnetostratigraphy: Llanvirn–Caradoc limestones of the Baltic platform. Geophysical Journal International 107, 171–184.
Torsvik, T.H., Van der Voo, R., Preeden, U., MacNiocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J.J., Domeir, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A., Cocks, R.M., 2012. Phanerozoic polar wander, palaeogeography and dynamics. Earth Science Reviews 114, 325–368.

Trower, E.J., Grotzinger, J.P., 2010. Sedimentology, diagenesis, and stratigraphic occurrence of giant ooids in the Ediacaran Rainstorm Member, Johnnie Formation, Death Valley region, California. Precambrian Research 180 (1–2), 113–124.
Van Alstine, D.R., Gillett, S.L., 1979. Paleomagnetism of the upper Precambrian sedimentary rocks from the Desert Range, Nevada. Journal of Geophysical Research 84, 4490–4500.
Van der Voo, R., 1990. The reliability of paleomagnetic data. Tectonophysics 184, 1–9.
Van Staal, C.R., Dewey, J.E., Mac Niocaill, C., McKerrow, W.S., 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In: Blundell, D.J., Scott, A.C. (Eds.), Lyell: The Past is the Key to the Present. Geological Society, London, Special Publications, 143, pp. 199–242.
Velikanov, V.A., 1985. The general Vendian section of Podolia. In: Sokolov, B.S., Fedonkin, M.A. (Eds.), The Vendian System. Nauka, Moscow, pp. 35–67 (in Russian).
Walderhaug, H.J., Torsvik, T.H., Halvorsen, E., 2007. The Egersund dykes (SW Norway): a robust Early Ediacaran (Vendian) palaeomagnetic pole from Baltica. Geophysical Journal International 168, 935–948.
Williams, H., 1995. Geology of the Appalachian–Caledonian orogen in Canada and Greenland. Ottawa, Geological Survey of Canada, Geology of North America, vol. F1 (944 pp.).
Wingate, M.T.D., Giddings, J.W., 2000. Age and paleomagnetism of the Mundine Well dyke swarm, Western Australia: Implications for an Australia–Laurentia connection at 755 Ma. Precambrian Research 100, 335–357.
Zijderveld, J.D.A., 1967. AC demagnetization of rocks: analysis of results. In: Collinson, D.W., Creer, K.M. (Eds.), Methods in Paleomagnetism. Elsevier, Amsterdam, pp. 254–286.