Gondwana Research 25 (2014) 159–169

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

GR focus review

Ediacaran–Early Ordovician paleomagnetism of Baltica: A review

Joseph G. Meert *

Department of Geological Sciences, 241 Williamson Hall, University of Florida, Gainesville, FL 32611, United States

ARTICLE INFO

Article history:
Received 11 October 2012
Received in revised form 13 February 2013
Accepted 17 February 2013
Available online 26 February 2013

Handling Editor: M. Santosh

Keywords:
Ediacaran
Cambrian
Paleogeography
Baltica
Paleomagnetism

ABSTRACT

The Ediacaran–Early Ordovician interval is of great interest to paleogeographer's due to the vast evolutionary changes that occurred during this interval as well as other global changes in the marine, atmospheric and terrestrial systems. It is; however, precisely this time period where there are often wildly contradictory paleomagnetic results from similar-age rocks. These contradictions are often explained with a variety of innovative (and non-uniformitarian) scenarios such as intertial interchange true polar wander, true polar wander and/or non-dipolar magnetic fields. While these novel explanations may be the cause of the seemingly contradictory data, it is important to examine the paleomagnetic database for other potential issues.

This review takes a careful and critical look at the paleomagnetic database from Baltica. Based on some new data and a re-evaluation of older data, the relationships between Baltica and Laurentia are examined for ~600–500 Ma interval. The new data from the Hedmark Group (Norway) confirms suspicions about possible remagnetization of the Fen Complex pole. For other Baltica results, data from sedimentary units were evaluated for the effects of inclination shallowing. In this review, a small correction was applied to sedimentary paleomagnetic data from Baltica. The filtered dataset does not demand extreme rates of latitudinal drift or apparent polar wander, but it does require complex gyrations of Baltica over the pole. In particular, average rates of APW range from 1.5° to 2.0°/Myr. This range of APW rates is consistent with 'normal' plate motion although the total path length (and its oscillatory nature) may indicate a component of true polar wander. In the TPW scenario, the motion of Baltica results in a back and forth path over the south pole between 600 and 550 Ma and again between 550 and 500 Ma. The rapid motion of Baltica over the pole is consistent with the extant database, but other explanations are possible given the relative paucity of high-quality paleomagnetic data during the Ediacaran–Cambrian interval from Baltica and other continental blocks.

A sequence of three paleogeographic maps for Laurentia and Baltica is presented. Given the caveats involved in these reconstructions (polarity ambiguity, longitudinal uncertainty and errors), the data are consistent with geological models that posit the opening of the Iapetus Ocean around 600 Ma and subsequent evolution of the Baltica–Laurentia margin in the Late Ediacaran to Early Ordovician, but the complexity of the motion implied by the APWP remains enigmatic.

Contents

---

* Tel.: +1 352 846 2414; fax: +1 352 392 9294.
E-mail address: jmeert@ufl.edu.

1342-937X/$ – see front matter © 2013 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.gr.2013.02.003

1. Introduction

The Ediacaran period (635–542 Ma; Knoll et al., 2006) is one of the more intriguing intervals 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'. There are myriad explanations for why the fossil record becomes richer (with larger organisms) during the Cambrian (see Meert and Lieberman, 2008 for a review). While there are proposals for both extrinsic (non-biological) and intrinsic (biological) triggers for the radiation, the paleogeography of the Ediacaran–Cambrian provided an important backdrop for the biological changes. The precise paleogeography for the Ediacaran–Cambrian is the subject of significant controversy particularly for Laurentia and Baltica (Meert et al., 1993, 1994; Kirschvink et al., 1997; Evans, 1998; Meert, 1999; Popov et al., 2002; Meert et al., 2003a; Nawrocki et al., 2004; Iglesia Llanos et al., 2005; McCausland et al., 2007; Meert et al., 2007; Pisarevsky et al., 2008; Abrajevitch and Van der Voo, 2010; McCausland et al., 2011). It has been argued that the Ediacaran 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.

This paper presents a review of paleomagnetic data from Baltica in an attempt to further constrain its paleogeographic history. This paper reviews each previously published paleomagnetic study and divides the results into groups of (1) highly reliable A grade poles; (2) seemingly reliable B-grade poles and (3) questionable C–D grade paleomagnetic poles. Highly reliable poles generally have field tests that demonstrate their primary nature, are part of the stable continent and are not likely to have suffered from inclination shallowing (see Tauxe and Kent, 2004; Tauxe et al., 2008). Inclination shallowing is relatively common in fine-grained red sandstones and results in paleolatitudes that are systematically lower than coeval igneous rocks (see Gilder et al., 2003). Inclination-shallowing 'error' is more pronounced at mid-latitudes and can be evaluated via the error formula of King (1955) where:

$$\tan(I_0) = f \tan(I_f)$$

(see Fig. 1).

The flattening factor (f) is equal to 1.0 for rocks that exhibit no inclination shallowing. Most experimental results show flattening values in the range from 0.4 to 0.55 (King, 1955; Tauxe and Kent, 1984; Hodych and Bijaksana, 1993) for clastic sedimentary rocks.

"B-class" poles have field tests that demonstrate their primary nature and are part of the stable continent but may be affected by inclination shallowing. 'C–D' class poles will fail to meet several traditional 'stability' criteria. For example, C–D results may not have field tests to constrain the age of magnetization, may not be located on the stable continent, may result from limited sampling or may show strong evidence of younger overprinting. There are certainly other schemes that can be applied to paleomagnetic data (e.g. Van der Voo, 1990); however, this simpler scheme is useful for evaluating the paleomagnetic data for Baltica during the Ediacaran–Cambrian interval. The Q-factor is included as an additional measure of reliability in the analysis.

Table 1 lists all known paleomagnetic studies for Baltica during the interval from 635 to 458 Ma. We include Early Ordovician data because they form a useful 'anchor-point' for evaluating plate motion rates required by the Ediacaran–Cambrian paleomagnetic data. The Early Ordovician mean pole falls at 25° N, 54° E (A95 = 10.9°; Torsvik and Trench, 1991; Smethurst et al., 1998; Khramov and Iosifidi, 2009).

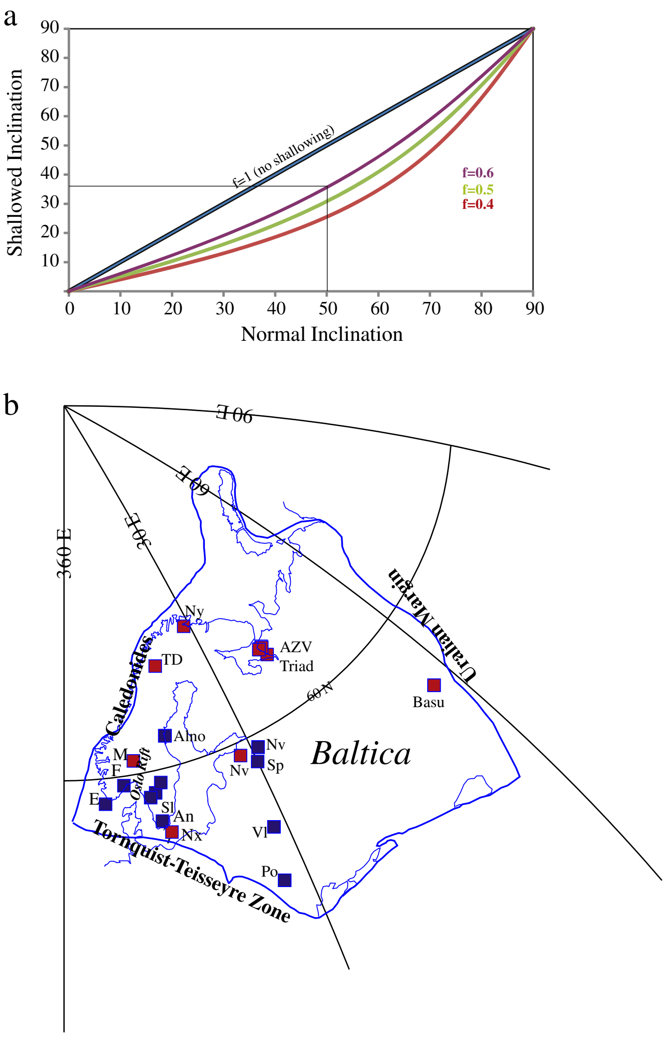

Fig. 1. (a) The effects of inclination shallowing on paleomagnetic data from sedimentary rocks. The effect is most pronounced for sedimentary rocks formed at intermediate latitudes. As an example, a sedimentary rock formed at ~31° latitude (50° inclination) would appear to have formed at 20° latitude (36° inclination). Inclination shallowing effects are shown for f = 1 (no shallowing), f = 0.6 (most common), f = 0.5 and f = 0.4. This paper applies a universal f = 0.6. (b) Map of Baltica showing the location of Ediacaran–Ordovician paleomagnetic studies discussed in this paper. Red squares show sedimentary units where inclination shallowing is suspected, blue squares are from units not affected by inclination shallowing. AZV Triad-Winter Coast and related studies; Ny = Nyborg Group; TD = Tornetrask–Dividal; Nv = Narva sedimentary rocks; Sp = St. Petersburg Limestone; Vl = Volhynia lavas; Po = Podolia; Nx = Nekso sandstone; An = Andarum; Sl = Swedish limestones; M = Moelv tillite; F = Fen Complex; E = Egersund dykes.

2. Quality review of previously published results

2.1. "A" Grade: highly reliable poles

The Egersund dyke (Fig. 1b; Walderhaug et al., 2007) pole falls at 31° N, 44° E (Fig. 2; Table 1) and the rocks are dated to 616 ± 3 Ma (U–Pb zircon, Bingen et al., 1998). The pole was considered primary on the basis of three arguments forwarded by the authors. The Egersund dykes have a positive baked contact test that includes a well-defined 'hybrid zone'. Biotite samples from the dykes were subjected to $^{40}Ar/^{39}Ar$ dating and produced an age of 609 ± 10 Ma that is statistically indistinguishable from the U–Pb age. Although the lack of disturbance in the argon systematics of biotite does not preclude remagnetization (see Meert et al., 2003b), there are at least two time intervals of deformation and reheating of the Baltic shield that may have reset magnetization. During the Late Silurian–Devonian (~420 Ma) the Baltic shield experienced the Caledonian orogeny (Hendricks and Redfield, 2005) and the

Table 1
Paleomagnetic poles from Baltica (Ediacaran–Early Ordovician).

Pole name	Class	Q[a]	Dec[b]	Inc[c]	FInc[d]	a95[e]	GLat[f]	GLon[g]	Plat[h]	Plon[i]	Age[j]
1. Swedish limestones	A	5	335	−52	–	13.4	58.3	13.9	3	35	458
2. Swedish limestones	A	5	116	67	–	9	58	13	30	55	475
3. Swedish limestones	A	6	138	62	–	5.1	59	15	18	46	475
4. Narva limestones	A	4	144	63	–	4	59	31	18	55	475
5. St Petersburg limestone	A	5	130.4	73.1	–	3.6	58	30	33	58	478
6. Narva sediments	C	5	106	54	*66.5*	5	59	28	22	87	500
7. Andarum—alum Shale	C	4	51	57	*68.7*	6.8	55.7	14	52	111	500
8. Tornetrask Fm/Divídal group	C	4	57	66	*75*	8.9	68.2	19.5	56	115	535
9. Nekso sandstone	C	3	194	−12	*−19.5*	7	55	15	40	177	545
10. Zolotitsa	B	6	298.9	37.7	*52.2*	2.3	65.5	40.0	32	293	550
11. Verkhotina	B	6	305	35.9	*50.3*	2.2	64.8	40.5	32	297	550
12. Volhynia lavas–Rafalivka	C	4	269	66	–	2.4	52.8	28.3	36	333	551
Volhynia Lavas–Bazaltovoye-5	C	3	114	−26	–	3.9	52.8	28.3	26	282	551
13. Winter Coast	B	6	279	41.3	*55.6*	3	65.5	39.8	24	312	555
14. Arkhangelsk–Zolotica	B	6	120	−31.7	*−43.5*	3.9	65.6	40.5	28	290	556
15. Podolia	C	6	132.2	−32.2	*−46.4*	5.5	48.7	27.5	40	276	560
16. Basu Formation (tc)	C	5	42	−37	*−51.5*	12.2	54.0	57.0	−1	007	560
17. Fen Complex	D	4	203	−49	–	8	59.3	9.3	57	152	583
18. Alnø steep	D	4	51.2	70.2	–	8.3	62.5	17.5	63	101	589
19. Alnø shallow	D	3	108	10.5	–	32.1	62.5	17.5	4	269	589
20. Alnø Piper	D	3	107.2	1.6	–	9.3	62.5	17.5	8	272	589
21. Egersund dykes	A	5	120	69	–	10	58.4	6.2	31	44	608
22. Moelv Tillite (i.s)	D	2	186	−54	*−66.4*	4.2	61.1	11.4	63	180	<610
23. Nyborg Formation	C	4	110	53	*65.7*	18	70.1	28.7	24	089	<635
Permo-Triassic poles											
24. Secondary components						9			59	153	~200
25. Secondary components						8			42	159	~265
26. Igneous rocks-Stable Europe						4			52	161	270

Notes: References by pole number (1, 2, 3) Torsvik and Trench (1991); (4) Khramov and Iosifidi (2009); (5) Smethurst et al. (1998); (6) Khramov and Iosifidi (2009); (7, 8) Torsvik and Rehnström (2001); Rehnström and Torsvik (2003); Bylund (1994); (9) Lewandowski and Abrahamsen (2003); (10, 11) Popov et al. (2005); (12) Nawrocki et al. (2004); (13) Popov et al. (2002); (14) Iglesia Llanos et al. (2005); (15) Iosifidi and Khramov, 2005; (16) Golovanova et al. (2011); (17) Meert et al. (1998); (18, 19) Meert et al. (2007); (20) Piper (1981); (21) Walderhaug et al. (2007); (22) this study, (23) Torsvik et al. (1995); (24, 25) Mean overprints from Khramov and Iosifidi (2009), (26) Mean from Dominguez et al. (2011).

Italics signifies F-corrected inclination.

[a] Q-value based on Van der Voo (1990).

[b] Declination.

[c] Inclination.

[d] Flattening corrected inclination (f = 0.6) for clastic sediments.

[e] Alpha-95 circle of 95% confidence about the mean direction.

[f] Site Latitude.

[g] Site Longitude.

[h] Paleomagnetic pole latitude.

[i] Paleomagnetic pole longitude.

[j] Age determination by pole (1–9, 15) fossils; (10–14) U–Pb zircon; (16–20) ^{40}Ar/^{39}Ar biotite; (21) U–Pb zircon and ^{40}Ar/^{39}Ar biotite; (16, 22, 23) Stratigraphic correlation.

Permo-Triassic interval witnessed the opening of the Oslo Graben (270–240 Ma; Torsvik et al., 1998; Dominguez et al., 2011;). The Egersund dyke pole does not fall near paleomagnetic poles that comprise the Siluro-Devonian loop or near Permo-Triassic poles (Fig. 2). Lastly, the authors argue that older units (~870 Ma) from localities close to the Egersund dykes show distinct magnetic directions precluding a widespread remagnetization event in the region.

It would appear that the Egersund dyke pole represents a strong candidate for an Ediacaran 'tie point' that will connect, via younger Ediacaran and Cambrian poles, to the Late Ordovician results described above. There is; however, one caveat to making an airtight case for the primary nature of the Egersund dyke pole. The Egersund dyke pole does resemble paleomagnetic directions corresponding to the Late Ordovician segment of the Baltica apparent polar wander path as does the older Rogaland Igneous Complex and Vest Agder Gneissic Complex combined pole (Fig. 2; Walderhaug et al., 2007). During the Early Ordovician, this region of Baltica was a passive margin facing the Ægir Sea and/or Iapetus Ocean (Torsvik et al., 2012) and thus it seems less likely that the region would be affected by deformation-related remagnetization.

The other A-poles in this study are of Early to Middle Ordovician in age (Table 1; Fig. 2) ranging from 458 to 478 Ma. These data yield a mean Early Ordovician pole at 21° N, 50° E (A95 = 14.4°).

2.2. "B" Grade paleomagnetic poles

Each of the poles discussed in this section is part of the stable Baltica continent and has evidence for their primary nature (field tests or reversal test), but may suffer from inclination shallowing (Table 1; Fig. 2). These results (Fig. 1b) are all from sedimentary rocks from the White Sea area of northern Russia, the Podolia region (Ukraine) and the Narva River region (near St. Petersburg Russia). The most consistent set of results come from Late Ediacaran (~550–555 Ma) sedimentary sequences along the Winter Coast region (Fig. 2; Popov et al., 2002; Iglesia Llanos et al., 2005; Popov et al., 2005). The AZV triad of poles (Archangelsk, Zolotitsa and Verkhotina) plot closely to one another although slightly displaced from the Winter Coast pole. Sedimentary sequences from the Podolia region of the Ukraine (Fig. 1b; Iosifidi and Khramov, 2005) although paleomagnetic data from Podolia are of lower reliability (Fig. 2).

Since these paleomagnetic poles are derived from studies of fine-grained sedimentary rocks, there is some concern about inclination shallowing in those sediments. One possible test for inclination shallowing is to compare coeval sedimentary and volcanic rocks (see Van der Voo and Torsvik, 2004). If there are systematic inclination differences between sedimentary rocks and coeval igneous rocks, then inclination shallowing is a concern and a correction can be applied to the

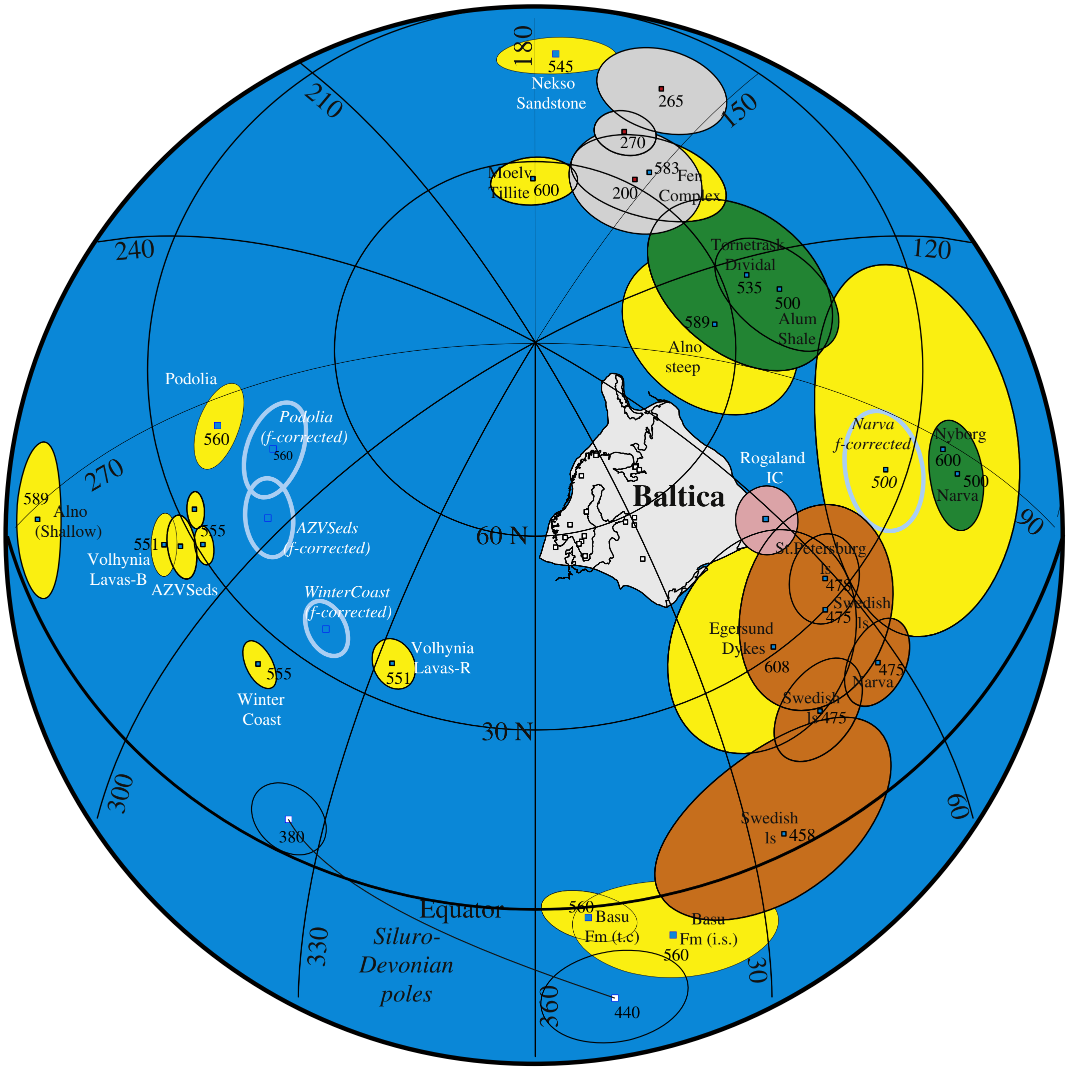

Fig. 2. Compilation of paleomagnetic poles from Baltica. Pink-shaded poles are Neoproterozoic age; yellow-shaded poles are Ediacaran age; green-shaded poles are Cambrian in age; orange-shaded are Ordovician age; gray-shaded poles are Permo-Triassic in age; black-unshaded poles are Siluro-Devonian in age. Light blue-unshaded poles are inclination-corrected poles (using f = 0.6). Exact coordinates can be found in Table 1.

sedimentary data. There are coeval igneous rocks from the Volhynia lavas (Ukraine), but they pose an interesting conundrum. One of the poles (Volhynia lavas-B, Table 1; Fig. 2) is indistinguishable from the AZV triad whereas the other (Volhynia lavas-R; Table 1, Fig. 2) shows steeper inclinations. Due to the limited number of cooling units sampled, the Volhynia lava results do not adequately average secular variation and cannot be used as an argument for or against inclination shallowing.

In an effort to evaluate inclination shallowing in the Archangelsk sediments, we attempted to use the elongation–inclination (E–I) method employed by Tauxe and Kent (2004) as applied to the Zolotica–Arkhangelsk results (Iglesia Llanos et al., 2005). The E–I method is based on a paleosecular variation model for the past 5 Ma and requires numerous 'spot' readings of the magnetic field in order to provide an adequate sample for comparison. In sedimentary rocks, each sample represents a 'spot-reading' of the field. Based on theoretical examples, Tauxe et al. (2008) show that for datasets with n < 100 sites, the confidence bounds on both E and I are large and estimates of flattening using this method are less reliable. Furthermore, the density of sampling must be high and 'sites' that incorporate more than one sample will invariably 'smooth' out the secular variation signal resulting in an underestimate of inclination shallowing (Kodama, 2012).

The Iglesia Llanos et al.'s (2005) study contains data from 140 sites covering a stratigraphic interval of ~9 m. In principle, this would meet the requirements of the E–I method, but there are several complicating factors. The complications arise due to the fact that some site means are determined by great-circle analysis, many stratigraphic intervals are represented by more than one sample and directional data are sometimes not fully resolved due to overlapping magnetite/hematite unblocking temperatures. Iglesia Llanos et al. (2005) base their overall mean on only 57 sites that show 'only fully normal or fully reverse directions'. The characteristic direction (Dec = 120.3°, Inc = −31.7° α_{95} = 3.9°, k = 22) in that study was isolated at temperatures > 620 °C.

A review of the data used in the Iglesia Llanos et al.'s (2005) study indicates that additional sites might be used to evaluate the overall mean direction. Using unblocking temperature (T_{ub}) as a criteria for limiting overlapping unblocking spectra, we compiled a liting of 96 sites where T_{ub} > 620 °C. In this analysis, approximately 96 sites were initially used to evaluate inclination shallowing. The mean direction of those 96 sites was Dec = 125°, Inc = −31° (α_{95} = 4.2°, k = 13; Fig. 3a). Fig. 3b shows the results of the E–I analysis using this dataset. The crossover point is at 54° (f ~0.4) with a range of f-values between 0.25 and 0.6 (E-range 1.300–1.865). The dispersion in this collection

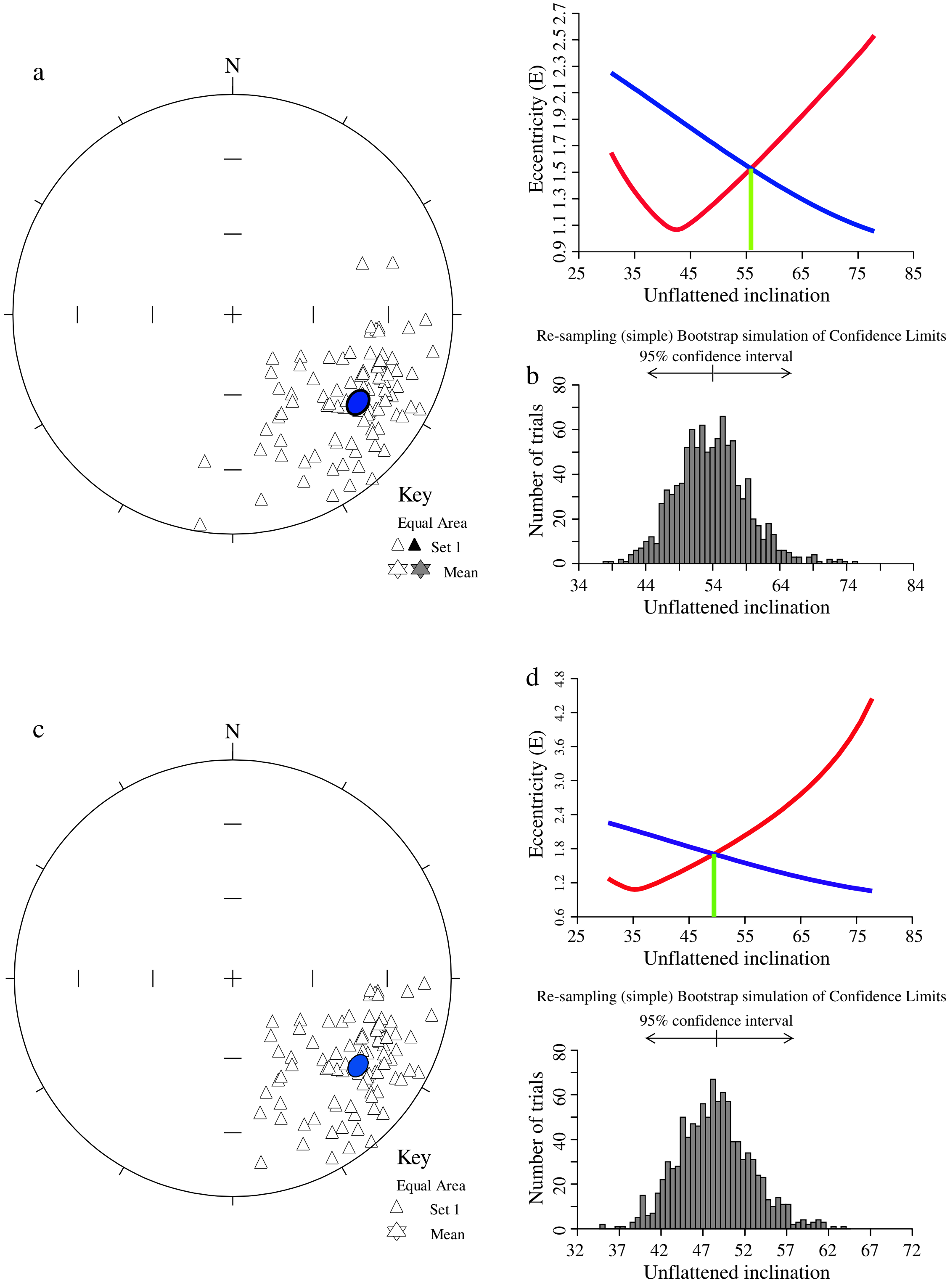

Fig. 3. Elongation–Inclination (E–I) test on the paleomagnetic results of Iglesia Llanos et al. (2005). (a) Distribution of mean directions for the study for sites with N≥2 and unblocking temperatures (T_{ub}) > 620 °C (b) Results of the eccentricity of the distribution versus unflattend inclination. The 'crossing' inclination is at 56° with a resultant flattening factor of 0.4, bottom figure shows a bootstrap simulation to determine the 95% confidence interval for the flattening factor (0.3–0.7) (c) distribution of mean directions for the study for sites with N≥2, unblocking temperatures (T_{ub}) > 620 °C and directions confined to the SE-quadrant; (d) Results of the eccentricity of the distribution versus unflattend inclination. The 'crossing' inclination is at 44° with a resultant flattening factor of 0.6, bottom figure shows a bootstrap simulation to determine the 95% confidence interval for the flattening factor (0.46–0.85).

(k = 13) is higher than in the mean (k = 22) reported by Iglesia Llanos et al. (2005) and suggests that overprinting of components may be problematic.

A second analysis was conducted by further restricting the dataset to only sites that fall in the southeastern quadrant (Fig. 3c) in an effort to limit dispersion and more closely approximate the mean in the original study. The mean of these 92 sites was Dec = 124.9°, −30.7° (α_{95} = 3.9°, k = 16). Fig. 3d shows the results of the E–I analysis using this dataset. The crossover point is at 49.5° (f~0.5) with a range of f-values between 0.34 and 0.65 (E-range 1.473–1.976).

Given the caveats stated above, the E–I analysis of the Zolotica results indicates that these sediments are affected by inclination shallowing with f-values ranging between F~0.3 and 0.7.

Due to the lack of dense sampling, we were unable to apply the E–I method to the other sedimentary sequences in Podolia or the Winter Coast sedimentary rocks (results 10, 11, 13 and 15 in Table 1). We thus followed the suggestion made by Torsvik et al. (2012) and corrected all results from clastic sediments using a 'conservative' estimate for flattening f = 0.6 (Fig. 1a). Flattening corrected poles are shown in Fig. 2 (light-blue shading). Note that after inclination shallowing is applied, the Podolia pole and the AZV triad mean pole overlap, but the pole from the Winter Coast sediments is still distinct. The Winter Coast pole does move closer to the Volhynia Lavas-R direction (Fig. 2).

The Late Cambrian Narva sediment pole (500 Ma) was also derived from fine-grained sediments and was corrected for inclination shallowing (f = 0.6; Fig. 2).

2.3. "C" Grade paleomagnetic poles

C-grade poles may have some use in paleogeographic reconstructions, but they are too poorly resolved to make a strong case for any particular geodynamic model. These poles should be viewed with extreme caution. C-poles may be useful in evaluating apparent polar wander paths, but only as complimentary points anchored by A or B poles. C-poles will generally have one or more complications that preclude their use as anchor poles along an APWP.

In reviewing paleomagnetic data from Baltica, there are five poles that retain a C-rating. Three of the five poles are derived from tectonically complicated regions. The Tornetrask/Divídal results (Torsvik and Rehnström, 2001; Rehnström and Torsvik, 2003) are derived from rocks along the Caledonian front (Fig. 1b). While this does not eliminate the pole from consideration, the proximity of the sampled locations to tectonically disturbed regions can cause complications in interpreting those results. As an example, the region may have suffered from vertical-axis rotations. The Tornetrask–Divídal pole can be rotated to bring it into alignment with A–B Cambrian/Ordovician poles, but additional information must be garnered from the region to evaluate the magnitude and sense of the rotation.

The Basu formation pole (Figs. 1b, 2; Golovanova et al., 2011) has several issues that preclude its use in any reconstruction or evaluation of Baltica's apparent polar wander path. First, the pole is derived from sedimentary sequences located along the margins of Baltica within the Bashkirian anticlinorium. Although generally considered to have formed proximal to mainland Baltica, the rocks may suffer from local vertical axis rotations. The study by Golovanova et al. (2011) argued against rotation on the basis of general agreement in declination from widely separated sites. The pole also passes a fold-test and a reversal test. The fold test only constrains the pole to be older than Late Paleozoic. The most significant issue for this pole is that it resembles Silurian poles from Baltica (tilt-corrected, Fig. 2). In addition, the age of the pole is poorly constrained to "Late Vendian" although a recent paper by Grazhdankin et al. (2011) argues for an age range between 567 and 548 Ma on the basis of stratigraphic correlation between well-dated and poorly-dated sections in the central and southern Urals.

The Nekso sandstone pole (Figs. 1b, 2; Lewandowski and Abrahamsen, 2003) of Cambrian age is derived from sedimentary units positioned in a horst block within the Caledonian deformational region between the Sorgenfrei–Tornquist Zone and the Tornquist–Teisseyre Zone on the island of Bornholm. The age of the Nekso sandstone is considered "Early Cambrian". Lewandowski and Abrahamsen (2003) assign an age of 545 Ma based on an older time scale. The current time scale would place deposition of the Nekso sandstone to > 530 Ma (pre-Tomottian). The Nekso sandstone pole is displaced from all other Cambrian poles of Baltica, but can be easily rotated onto the Permo-Triassic suite of poles using a ~10° vertical axis rotation.

The remaining C-poles are classified as such because they are based on very few samples. The Andarum limestone pole (Figs. 1b, 2; Torsvik and Rehnström, 2001) is calculated from 11 samples. The Volhynia lavas (mentioned above, Nawrocki et al., 2004) yielded two very disparate directions (high latitude and low latitude). Two flows yielded the low-latitude direction (Bazaltovoye-5) and the high-latitude results from the Rafalivka resulted from a study of three flows and one tuff layer. Age constraints (~551 Ma) were based on U–Pb zircon determinations from overlying tuffs with the assumption that the volcanic activity was synchronous with the emplacement of the lavas and tuffs. The significance of these results is problematic. The low-latitude Volhynia direction corresponds well to the AZV mean cited earlier whereas the high-latitude result is slightly displaced from the f-corrected Winter Coast pole (Fig. 2). The Andarum limestone (Alum) VGP is distinct from more well-defined poles from Baltica (Narva pole; Fig. 2), but due to the very limited sample size, it is preliminary to completely reject this result. Thus, all five of these results are classified as C-poles and should not be used as anchor points in Baltica's APWP.

2.4. "D" Grade paleomagnetic poles

Poles that received a D-grade in this review should not be used for paleogeographic reconstructions. The rationale for rejecting each of these poles is given below.

The Fen pole (Figs. 1b, 2; most recently summarized by Meert et al., 1998) is often-cited as a reliable pole in previous works in spite of the fact that it resembles Permo-Triassic poles from Baltica. The main argument favoring a primary nature for the remanence in the Fen Complex was three-fold. First, the remanence was steeper than the extant Permo-Triassic directions available at the time (albeit only slightly so). Secondly, the ^{40}Ar/^{39}Ar system in biotite and phlogopite was not reset in the dykes suggesting that the region had not been significantly heated. Lastly, the fact that the hematite-bearing Rødberg sediments carried a stable remanence also argued against significant reheating in the region. Nevertheless, there were no stability tests for the Fen result leading the authors to caution using the Fen pole as a key pole in Neoproterozoic reconstructions.

In an effort to provide some additional paleomagnetic data for Baltica during a broadly coeval interval, samples of the Moelv tillite (reddish matrix) were collected from the Hedmark Group near the town of Moelv (Fig. 1b). The age of the Moelv tillite is poorly constrained; however, Bingen et al. (2005) obtained detrital zircons from the underlying Rendalen formation with ages as young as 620 Ma establishing an age for the Moelv tillite <620 Ma. The Moelv is also overlain (in some regions) by Cambrian-age Alum shales or the early Cambrian Vardal sandstone (Nystuen, 2008). This would restrict the age of the Moelv tillite to between 620 and 540 Ma. Bingen et al. (2005) argue that glaciation in the Moelv unit was part of the Gaskiers event at around 580 Ma.

Paleomagnetic samples from the Moelv tillite were drilled in the field using a gasoline-powered drill and cut into standard-sized cores for paleomagnetic study. They were stepwise thermally demagnetized and measured on a 2-G cryogenic magnetometer at the University of Florida (for complete methods see Malone et al., 2008). Most samples were unstable and yielded either present-day field directions or random components. A small suite of samples from two sites with different bedding attitudes yielded stable components (Fig. 4a, b). The two sites yielded a well-grouped in-situ mean direction with Dec = 186°, Inc = −55° (k = 140, a95 = 4.7°; Fig. 4c) and a poorly-grouped tilt-corrected mean with a Dec = 176°, Inc = +20° (k = 14, a95 = 15.5°; Fig. 4d). Although there are too few samples for a statistically significant fold test, the data are clearly better grouped in geographic coordinates (Fig. 4c). This argues strongly for a post-folding magnetization. Folding and thrusting in the region were of Caledonian-age (Siluro-Devonian). In addition, further rotation took place during the opening of the Oslo Rift during the Permian and Triassic. Fig. 4e compares the virtual geomagnetic pole (VGP) from the Moelv, the Fen pole and Permo-Triassic poles from Baltica (Iosifidi

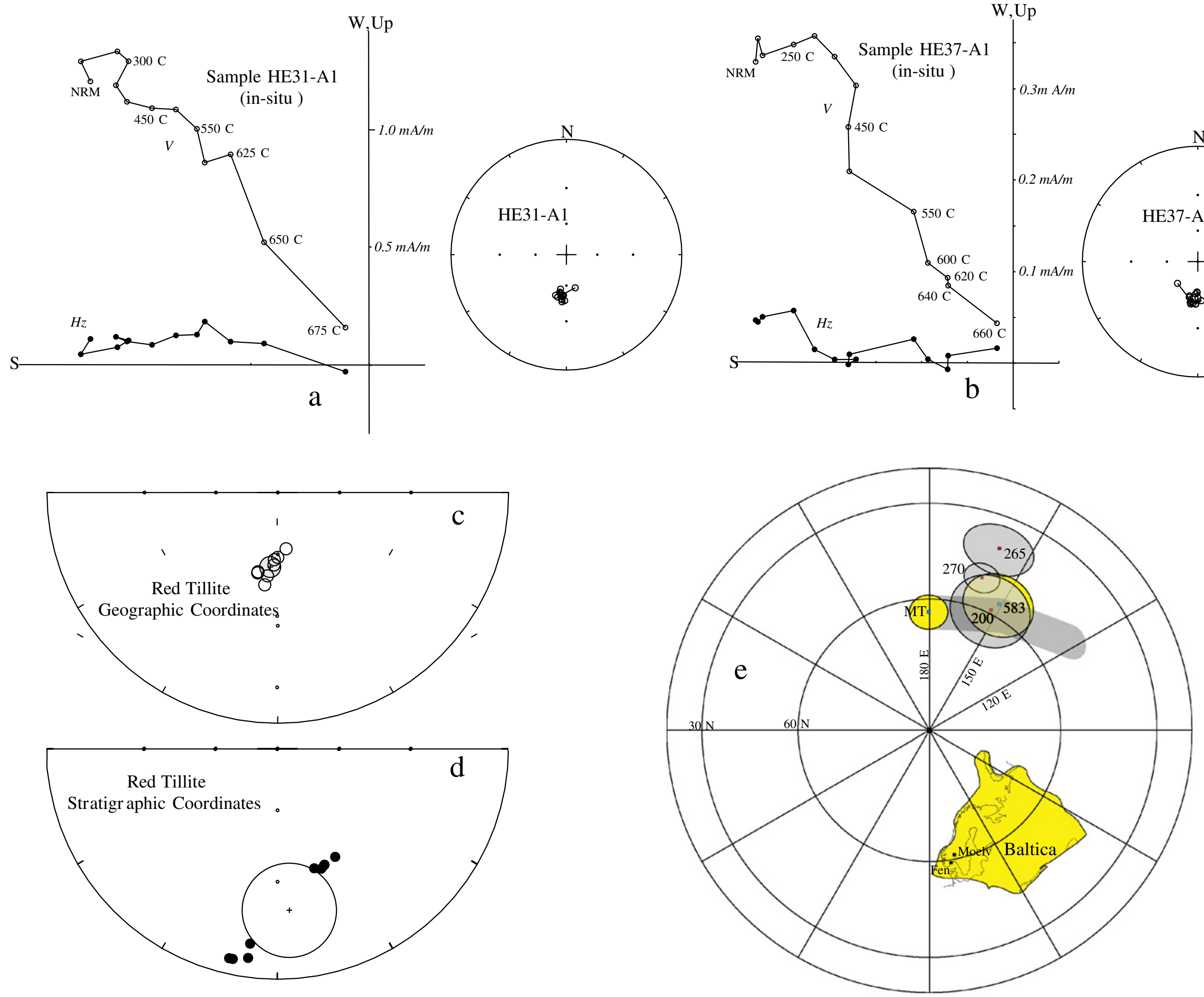

Fig. 4. (a) Moelv tillite sample HE-31A1 in-situ demagnetization and stereo diagram showing a high-temperature direction to the south and intermediate up (negative) inclination; (b) Moelv tillite sample HE-37A1 in-situ demagnetization and stereo diagram showing a high-temperature direction to the south and intermediate up (negative) inclination; (c) In-situ stereoplot of Moelv tillite sample high-temperature components from two sites with different bedding attitudes; (d) Tilt-corrected stereoplot of Moelv tillite sample high-temperature components from two sites with different bedding attitudes; (e) VGP of the in-situ Moelv directions, the Fen Complex pole and Permo-Triassic poles from Baltica. The shaded region represents a swathe of possible pole locations given potential rotation within the Oslo Rift.

and Khramov, 2005; Dominguez et al., 2011;). The Moelv pole is slightly displaced from the Permo-Triassic results, but it can be brought into alignment with the poles with a slight rotation. The Fen pole is also in close agreement with the Permo-Triassic results. Given the similarity of both the Fen and the in-situ Moelv VGP to these Permo-Triassic results, it is very likely that both the Moelv and Fen regions were affected by tectono-thermal events associated with the opening of the Oslo Rift and should no longer be used in Neoproterozoic reconstructions.

The other poles receiving a “D” grade are all derived from the Alno Complex in Sweden (Piper, 1981; Meert et al., 2007). Meert et al. (2007) noted the complexity in the magnetic signatures in the samples and the arbitrary nature of assigning a particular component to a larger mean. The same complexity was also noted in the early study by Piper (1981).

3. Discussion and implications

After a careful review of paleomagnetic data from Baltica, there are constraints on only three intervals of time during the Ediacaran–Ordovician. Although these anchor points provide a useful starting point for analyzing Baltica's motion, even the best poles are not without issues. The Egersund dyke pole (608 Ma) overlaps with younger Ordovician poles (Fig. 2). Late Ediacaran (555–550 Ma) poles are derived from sedimentary sequences that might suffer from inclination shallowing. Late Cambrian–Middle Ordovician poles appear to be the most consistent results from Baltica.

The following discussion takes a conservative approach with the available data in an effort to test various hypotheses regarding Ediacaran–Cambrian paleogeography. When applying a strong filter to the paleomagnetic data, there are tie-points at ~610 Ma, 550 Ma and 500 Ma. These intervals cover the time period where rapid APW, rapid drift rates and non-dipolar fields have been proposed on a global basis (Meert et al., 1993; Kirschvink et al., 1997; Evans, 1998; Abrajevitch and Van der Voo, 2010).

While outside the scope of this paper, there are numerous controversies surrounding Ediacaran paleomagnetic data from Laurentia (see Abrajevitch and Van der Voo, 2010; McCausland et al., 2011 for a discussion). In spite of these controversies, there are similar-aged poles for Laurentia that would meet the “A–B” criteria employed in this paper (Table 2). Where appropriate, Baltica is shown in its paleoposition using original paleomagnetic data and f-corrected data.

The Long Range dyke pole (Murthy et al., 1992) falls at 19° N, 355° E (A95 = 14.1°) and is dated to 615 ± 2 Ma (U–Pb zircon and baddeleyite; Kamo et al., 1989; Kamo and Gower, 1994). These dykes are thought to

Table 2
Paleomagnetic data and Euler poles for reconstructions.

Pole name	Plat	Plong	A95	Age
Long Range dykes	19 N	355 E	14.1	615 ± 2 Ma
Skinner Cove	16 S	338 E	7	550 + 3/− 2 Ma
Cambro-Ordovician	6 S	342 E	6.7	500–470 Ma

Notes: Long Range dykes pole from Hodych et al. (2004) and Murthy et al. (1992); Skinner Cove from McCausland and Hodych (1998); Mean Cambrian from Meert (1999) corrected for flattening (f = 0.6).

610 Ma reconstruction Euler poles; Laurentia: 21.3 N, 118 E, +121.7; Baltica: 0 N, 314 E, −121.

550 Ma reconstruction Euler poles: Laurentia: 14.3 N, 208.9 E, −69; Baltica (f): 0 N, 206 E, −130.3; Baltica (a): 0 N, 203 E, −121.

500 Ma reconstruction Euler poles: Laurentia: 16.6 N, 94 E, +86.4; Baltica (f): 26.8 N, 320.5 E, −129.1; Baltica (a): 6.6 N, 347 E, −113.2. Rock units used for the 500 Ma reconstruction for Laurentia can be found in Torsvik et al. (2012; Table 1); Tablehead Mtn, St. George Group, Oneota dolomite, Moores Hollow, Morgan Creek, Point Peak, Taum Sauk, Royer dolomite, Florida Mountains, Tapeats sandstone (Van der Voo et al., 1976; Elston and Bressler, 1977; Dunn and Elmore, 1985; Jackson and Van der Voo, 1985; Loucks and elmore, 1986; Deutsch and Prasad, 1987; Nick and Elmore, 1990; Farr and Gose, 1991).

mark the onset of rifting and the opening of the Iapetus Ocean between Baltica and Laurentia. Fig. 5a shows a possible paleogeographic reconstruction between Baltica and Laurentia using the Long Range dyke pole and the nearly coeval Egersund dykes pole discussed above. The paleomagnetic data are latitudinally consistent with a connection between Baltica and Laurentia at the time of Iapetus Ocean opening.

A reconstruction at 550 Ma is somewhat more problematic from the Laurentian side. The only pole available is derived from the Skinner Cove volcanics. The Skinner Cove volcanics are found in an allochthonous block in western Newfoundland. McCausland and Hodych (1998) and Hodych et al. (2004) argue that these volcanic rocks can be used as a proxy for Laurentia paleolatitudes because they formed near the Laurentian margin. Hodych et al. (2004) analyzed the age distributions from zircons extracted from more felsic members of the volcanic rocks. They found three populations with ages of 550 Ma, 1000 Ma and 1500–1600 Ma. These same age groups are found in Laurentian crust nearby and provide additional evidence that the Skinner Cove volcanic pole can be used to establish the paleolatitude of Laurentia. Baltica at 550 Ma can be positioned according to a mean pole derived from sedimentary sequences in the White Sea region (poles 10, 11 and 14 in Table 1). An average pole from this cluster falls at 31°N, 293° E (A95 = 5.8°) and an f-corrected mean pole at 40.3° N, 296° E (A95 = 5.7°). The reconstruction is shown in Fig. 5b. Due to the allochthonous nature of the Skinner Cove pole, only the latitude (not the orientation) of Laurentia can be fixed. In this reconstruction, the Skinner Cove volcanics are positioned at 19° S and Laurentia is slightly rotated so that the former conjugate margins (observed in the 610 Ma reconstruction) are more aligned.

The Cambrian reconstruction between Baltica and Laurentia in Fig. 5c is derived from a mean Laurentian pole from (see Meert, 1999) and is based on several studies of sedimentary rocks (see Table 2). This pole (6° S, 342° E) is corrected for inclination shallowing. The position of Baltica is placed according to an inclination-corrected pole for the Narva sediments at 33.4° N, 75.5° E.

The paleomagnetic data for Baltica can also be represented in terms of paleolatitudinal changes. A proper analysis of paleolatitudinal change requires detailed knowledge of the APWP. Given the paucity of high-quality data for Baltica, certain assumptions regarding the polarity of the poles and the trajectory of the path are required. For simplicity, all poles shown in Fig. 2 are assumed to be south poles. Fig. 6 shows possible great circle (i.e. minima) paths between the A and B pole tie points. Longer and more complex APWP's are permissible, but this conjecture provides a useful basis for discussion as the 'simplest' path.

Fig. 7a shows the paleolatitude of central Baltica (60 N, 30 E) based on the f-corrected and non-corrected paleomagnetic poles in Table 1. Fig. 7b and c shows the possible migration of Baltica 'over the pole' between 608 and 550 Ma and again between 550 and 500 Ma.

Latitudinal velocities do not, of course, give a full geodynamic picture of Baltica's motion during the Ediacaran–Ordovician interval especially since the extant paleomagnetic record is sparsely populated. In this case, it is more apropos to look at apparent polar wander rates for Baltica during the Ediacaran–Ordovician interval (Fig. 6). APW rates are a summation of the latitudinal and rotational motions of the continent and therefore tend to be higher than purely latitudinal rates. Using the revised poles in Table 1, the average APW rate from Baltica ranges between 10 cm/year (500–475 Ma) and 20 cm/year (550–500 Ma). These average rates, while fast, are not extreme and can be explained by normal plate motions on the globe or by a combination of normal plate motion and a smaller component of true polar wander.

Although individual segments of the APWP can be explained via normal, albeit fast, plate motions, the back and forth oscillation of the APWP between 608 and 550 Ma (~82°, 1.4°/Myr) and between 550 and 500 Ma (~97°, 1.94°/Myr) is more difficult to explain. These APW lengths are consistent with the magnitude of motion required by IITPW, but at present we cannot determine the exact time or duration of the APW motion.

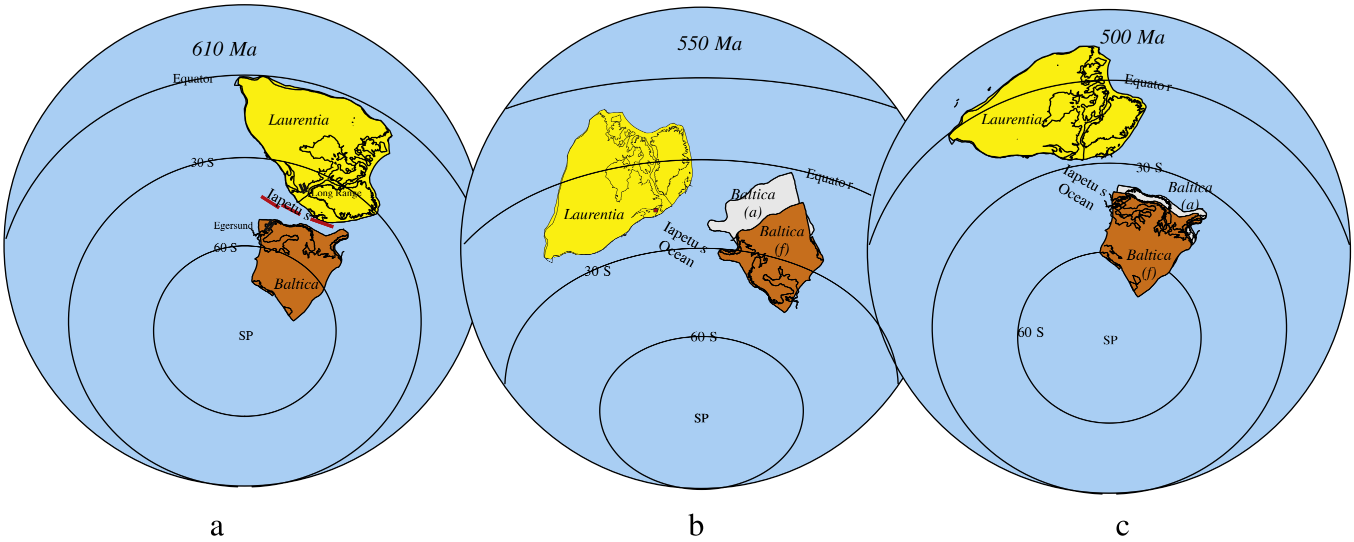

Fig. 5. (a) Reconstruction of Baltica and Laurentia at ~610 Ma; (b) Reconstruction of Baltica and Laurentia at 550 Ma; (c) Reconstruction of Baltica and Laurentia at 500 Ma. Gray-shaded continents are not corrected for inclination shallowing. F-corrected positions for Baltica contain the f-label. (d) Baltica's 608–550 Ma journey 'over the pole' and (e) Baltica's 550–500 Ma journey 'back over the pole'. Anchor points are tied by A & B poles, intermediate 'polar' positions are based on hypothetical path between poles given in Fig. 7.

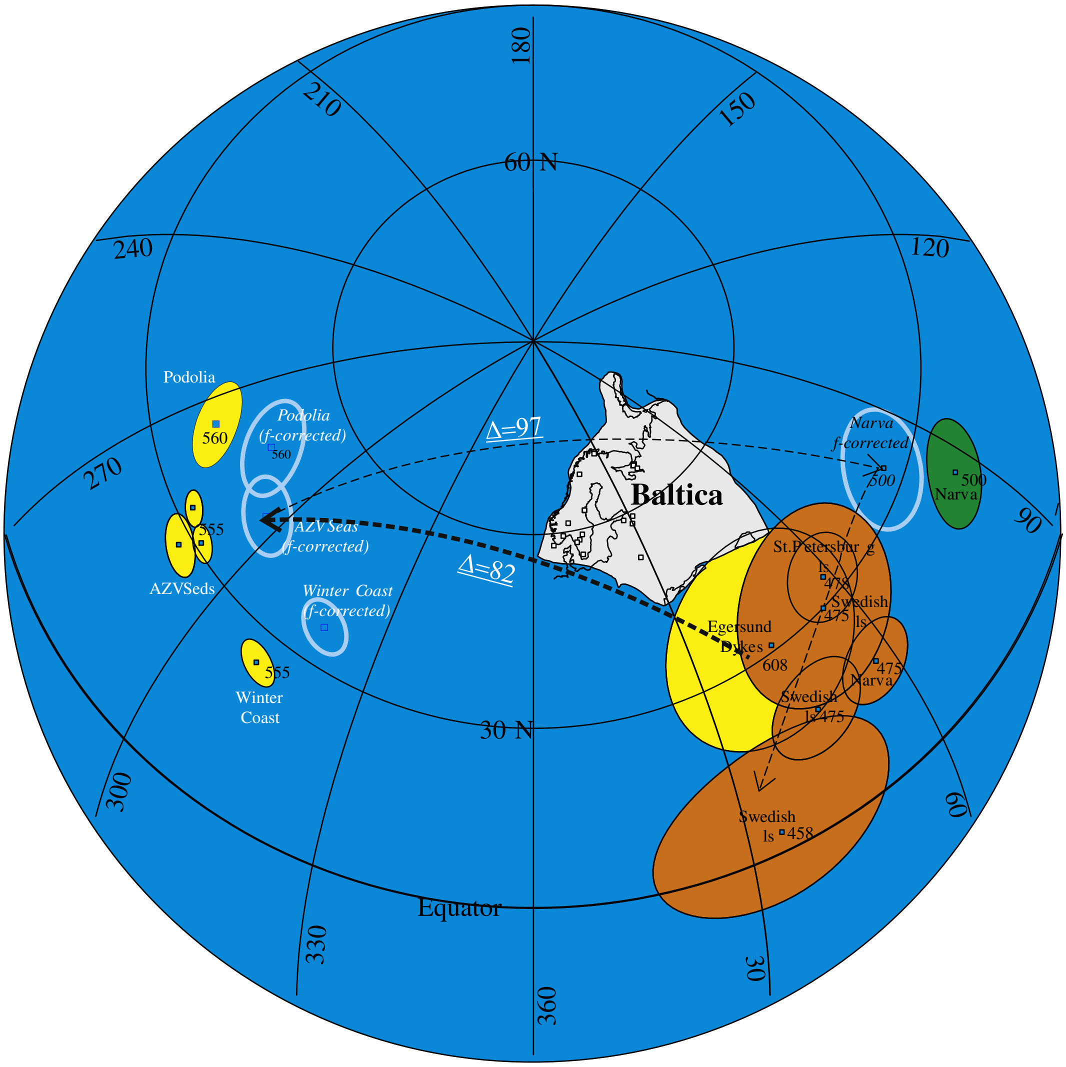

Fig. 6. A–B poles from Baltica (Table 1) showing the proposed APWP during the Ediacaran–Ordovician interval. The two lengthy segments from 608 to 550 Ma (Δ=82°) and from 550 to 500 Ma (Δ=97°) are denoted by dashed lines. Other shading/symbols are the same as Fig. 2.

While the *total* oscillation is of the correct magnitude, the *average* rates of change (<2°/Myr) are similar to those observed in the Phanerozoic and do not, in and of themselves, require significant TPW (Torsvik et al., 2012). On the other hand, if the path lengths reflect TPW or IITPW, then the same relative magnitude of APW should be found in other continents. For the younger interval (550–500 Ma), there are no complementary large swings in the APWP's of Laurentia or Australia required by the IITPW hypothesis (Hodych et al., 2004; Schmidt and Williams, 2010). Data from other continents for the older interval (608–550 Ma) are lacking or contradictory (see McCausland et al., 2011).

It is more difficult to use these data to evaluate the equatorial dipole scenario proposed by Abrajevitch and Van der Voo (2010). In order to fully describe the magnetic field during the Ediacaran–Cambrian interval a robust global dataset is required. At the same time, part of the rationale for proposing an oscillatory magnetic field was due to the contradictory nature of the Ediacaran–Cambrian dataset. For example, Abrajevitch and Van der Voo's analysis of the Baltica dataset relied on coeval, but disparate Ediacaran poles from the Fen Complex (Norway) and the Alno Complex (Sweden). Given that the Fen Complex pole is very likely a remagnetization and that many of the other poles considered in their analysis are problematic (e.g. too few samples, lack of evidence for primary magnetization, inclination shallowing), any non-dipole field explanation must draw on better resolved paleomagnetic data from other continents.

4. Conclusions

The Ediacaran–Cambrian interval is of great interest to paleogeography due to the vast evolutionary changes of that time interval as well as other global changes in the marine, atmospheric and terrestrial systems (see Meert and Lieberman, 2008). One of the main problems with Ediacaran paleomagnetism is that there are often wildly contradictory results from similar-age rocks. These contradictions are often explained with a variety of innovative (and non-uniformitarian) scenarios such as intertial interchange true polar wander and non-dipolar magnetic fields. While these novel explanations may be the cause of the seemingly contradictory data, it is important to examine the database for possible problems.

This review has taken a careful look at the database for Baltica and applied a conservative filter to the data. New data from the Hedmark Group (Norway) suggests that the Fen Complex pole was remagnetized during the opening of the nearby Oslo graben. Data from clastic sedimentary units from Baltica may be variably affected by inclination shallowing (Torsvik et al., 2012) and therefore a small correction was applied to these sedimentary paleomagnetic data. In spite of the conservative approach taken, the filtered dataset requires a complex tectonic scenario to explain the back and forth motion of Baltica in the Ediacaran–Ordovician interval. Perhaps the most intriguing feature of the dataset is the oscillation (~90°) from 608 to 550 and again from 550 to 500 Ma that may reflect some magnitude of true polar wander or additional

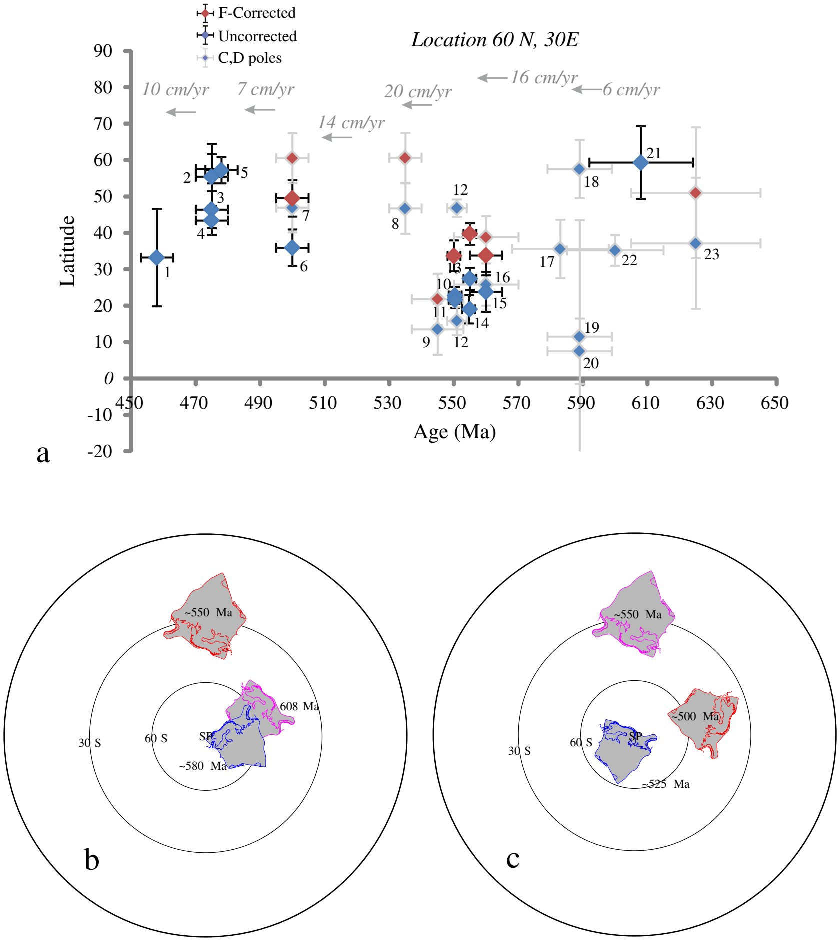

Fig. 7. (a) Paleolatitude diagram based on the poles in Table 1. Paleolatitudes are calculated for a central location in Baltica (60° N, 30° E). In this diagram, blue diamonds are latitudes uncorrected for inclination shallowing; red diamonds are inclination-corrected paleolatitudes. Light-gray shading is for C–D poles. Error bars are based on A95 values (latitudinal position) and age uncertainty. Average latitudinal rates of motion for major intervals are denoted by arrows and rates (cm/year). These rates assume a Baltica motion 'over the pole' between 608 and 550 Ma and again from 550 to 500 Ma as sketched. (b, c) Baltica's possible oscillatory 'over the pole' journey during the Ediacaran–Cambrian interval.

'atectonic' explanation. A more robust evaluation of true polar wander events and/or semi-stable departures from a dipole field requires a robust global dataset that is currently unavailable for the Ediacaran interval.

A sequence of three paleogeographic maps for Laurentia and Baltica is presented. Given the caveats involved in these reconstructions (polarity ambiguity, longitudinal uncertainty and errors), we do note that the data are consistent with geological models that posit the opening of the Iapetus Ocean around 600 Ma and subsequent evolution of the Baltica–Laurentia margin in the Late Ediacaran to Cambrian interval, but the complexity of that motion (using the chaotic Baltica APWP) is problematic.

Acknowledgments

This research was supported by NSF grant EAR11-19038 to Joseph Meert. I wish to thank Phil McCausland and Eric Tohver for raising excellent points that helped improve the manuscript. This paper is dedicated to my high school science teacher, Mr. Paul Ahlstrom who passed away on January 24, 2013 after a lengthy illness. Mr. Ahlstrom inspired my curiosity and influenced a great many young lives.

References

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

Bingen, B., Demaiffe, D., van Breeman, O., 1998. The 616 Ma Egersund basaltic dyke swarm, SW Norway, and the Late Neoproterozoic opening of the Iapetus Ocean. Journal of Geology 106, 565–574.

Bingen, B., Griffin, W.L., Torsvik, T.H., Saeed, A., 2005. Timing of Late Neoproterozoic glaciation by detrital zircon geochronology in the Hedmark Group, southest Norway. Terra Nova 17, 250–258.

Bylund, G., 1994. Palaeomagnetism of Vendian–Early Cambrian sedimentary rocks from E. Finnmark, Norway. Tectonophysics 231, 45–57.

Deutsch, E.R., Prasad, J.N., 1987. Ordovician paleomagnetic results from the St. George and Tablehead carbonates of western Newfoundland. Canadian Journal of Earth Sciences 24, 1785–1986.

Dominguez, A.R., Van der Voo, R., Torsvik, T.H., Hendricks, B.W.H., Abrajevitch, A., Domeir, M., Larsen, B.T., Rousse, S., 2011. The 270 Ma paleolatitude of Baltica and its significance for Pangea models. Geophysical Journal International 186, 529–550.

Dunn, W.J., Elmore, R.D., 1985. Paleomagnetic and petrographic investigation of the Taum Sauk limestone, southeast Missouri. Journal of Geophysical Research-B 90, 11,469–11,483.

Elston, D.P., Bressler, S.L., 1977. Paleomagnetism and polarity zonation from Cambrian and Devonian strata of Arizona. Earth and Planetary Science Letters 36, 423–433.

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

Farr, M.R., Gose, W.A., 1991. Paleomagnetism of the Cambrian Moore Hollow Group, Texas: evidence for a primary magnetization carried by detrital magnetite. Journal of Geophysical Research-B 96, 9895–9907.

Gilder, S., Chen, Y., Cogne, J., Tan, X., Courtillot, V., Sun, D., 2003. Paleomagnetism of Upper Jurassic to Lower Cretaceous volcanic and sedimentary rocks from the western Tarim Basin and implications for inclination shallowing and absolute dating of the M–O (ISEA) chron. Earth and Planetary Science Letters 206, 586–600.

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. Izvestiya, Physics of the Solid Earth 47, 623–635.

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.

Hendricks, B.W.H., Redfield, T.F., 2005. Apatite fission track and (U–Th)/He data from Fennoscandia: an example of underestimation of fission track annealing in apatite. Earth and Planetary Science Letters 236, 443–458.

Hodych, J.P., Bijaksana, S., 1993. Can remanence anisotropy detect paleomagnetic inclination shallowing due to compaction? A case study using Cretaceous deep-sea limestones. Journal of Geophysical Research-B 22,429–22,441.

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., Abalmassova, A., 2005. Palaeomagnetic data from Ediacaran (Vendian) sediments of the Arkhangelsk region, NW Russia: an alternative apparent polar wander path of Baltica for the Late Proterozoic–Early Palaeozoic. Earth and Planetary Science Letters 240, 732–747.

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

Jackson, M., Van der Voo, R., 1985. A lower Ordovician paleomagnetic pole from the Oneata dolomite, upper Mississippi Valley. Journal of Geophysical Research 90, 10449–10461.

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

Kamo, S.L., Heaman, L.M., Lumbers, S.B., 1989. Birthdate for the Iapetus Ocean? A precise U–Pb zircon and baddeleyite age for the Long Range dykes, southeast Labrador. Geology 17, 602–605.

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 Solid Earth 45, 465–481.

King, R.F., 1955. The remanent magnetism of artificially deposited sediments. Monthly Notices Royal Astronomical Society Geophysics Supplement 7, 115–134.

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

Knoll, A.H., Walter, M.R., Narbonne, G.M., Christie-Blick, N., 2006. The Ediacaran period: a new addition to the geologic time scale. Lethaia 39, 13–30.

Kodama, K.P., 2012. Paleomagnetism of Sedimentary Rocks: Process and Interpretation. John Wiley and Sons, U.K.(177 pp.).

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-B 108. http://dx.doi.org/10.1029/2002JB002281.

Loucks, V., Elmore, R.D., 1986. Absolute dating of dedolomitazation and the origin of magnetization in the Cambrian Morgan Creek limestone, central Texas. Bulletin of the Geological Society of America 97, 486–496.

McCausland, P.J.A., Hodych, J.P., 1998. Paleomagnetism of the 550 Ma Skinner Cove volcanics of western Newfoundland and the opening of the Iapetus. 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.

McCausland, P.J.A., Hankard, F., Van der Voo, R., Hall, C.M., 2011. Ediacaran paleogeography of Laurentia: paleomagnetism and 40Ar/39Ar geochronology of the Baie des Moutons syenite, Quebec. Precambrian Research 187, 58–78.

Malone, S.J., Meert, J.G., Banerjee, D.M., Pandit, M.K., Tamrat, E., Kamenov, G.D., Pradhan, V.R., Sohl, L.E., 2008. Paleomagnetism and detrital zircon geochronology of the Upper Vindhyan sequence, Son Valley and Rajasthan, India: A ca. 1000 Ma closure age for the Purana basins? Precambrian Research 164, 137–159.

Meert, J.G., 1999. A paleomagnetic analysis of Cambrian true polar wander. Earth and Planetary Science Letters 168 (1–2), 131–144.

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., Tamrat, E., 2004. A mechanism for explaining rapid continental motion in the Late Neoproterozoic. In: Eriksson, et al. (Ed.), The Precambrian Earth: Tempos and Events. Developments in Precambrian Geology, 12. Elsevier, Amsterdam, pp. 255–266.

Meert, J.G., Van der Voo, R., Powell, C. McA, Li, Z.X., McElhinny, M.W., Chen, Z., Symons, D.T.A., 1993. A plate tectonic speed limit? Nature 363, 216–217.

Meert, J.G., Van der Voo, R., Payne, T.P., 1994. Paleomagnetism of the Catoctin Volcanic province: a new Vendian–Cambrian apparent polar wander path for North America. Journal of Geophysical Research 99, 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., Endale, T., Spearman, J., 2003a. Non-dipole fields and inclination bias: insights from a random walk analysis. Earth and Planetary Science Letters 214, 395–408.

Meert, J.G., Nedelec, A., Hall, C., 2003b. The stratoid granites of central Madagascar: paleomagnetism and further age constraints on Neoproterozoic deformation. Precambrian Research 120, 101–129.

Meert, J.G., Walderhaug, H.J., Torsvik, T.H., Hendricks, B.W.H., 2007. Age and palaeomagnetic signature of the Alno carbonatite complex (NE Sweden): additional controversy for the Neoproterozoic position of Baltica. Precambrian Research 154, 159–174.

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, 309–316.

Nick, K.R., Elmore, R.D., 1990. Paleomagnetism of the Cambrian Royer dolomite and Pennsylvanian Collings Ranch Conglomerate, southern Oklahoma: an early Paleozoic magnetization and nonpervasive remagnetization by weathering. Bulletin of the Geological Society of America 102, 1517–1525.

Nystuen, J.P., 2008. Neoproterozoic Moelv tillite and the Hedmark Basin, the Mjosa area, South Norway, 33rd IGC Excursion Guide #101, (59 pp.).

Piper, J.D.A., 1981. Magnetic properties of the Alnon Complex. Geoligiska Foreningen i Stockholm Forhandlinger 103, 9–15.

Pisarevsky, S.A., Murphy, J.B., Cawood, P.A., Collins, A.S., 2008. Late Neoproterozoic and Early Cambrian paleogeography: models and problems. In: Pankhurst, et al. (Ed.), West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region: Geological Society of London Special Publication, 294, pp. 9–31.

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-B 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, 1–29.

Rehnström, E.F., Torsvik, T.H., 2003. Cambrian sediments and Proterozoic granites in the Dividalen–Torneträsk area, northern Scandinavia: paleomagnetism and U–Pb geochronology. Geoligiska Foreningen i Stockholm Forhandlinger 125, 131–138.

Schmidt, P., Williams, G.E., 2010. Ediacaran palaeomagnetism and apparent polar wander path for Australia: no large true polar wander. Geophysical Journal International 182, 711–726.

Smethurst, M.A., Khramov, A.N., Pisarevsky, S.A., 1998. Paleomagnetism of the Lower Ordovician Orthoceras limestone, St. Petersburg and a revised drift history for Baltica in the early Paleozoic. Geophysical Journal International 133, 44–56.

Tauxe, L., Kent, D.V., 1984. Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redepositiomn sediments. Geophysical Journal of the Royal Astronomical Society 76, 543–561.

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., et al. (Ed.), Timescales of the Paleomagnetic Field, 145. American Geophysical Union, Washington, D.C, pp. 101–116.

Tauxe, L., Kodama, K.P., Kent, D.V., 2008. Testing corrections for paleomagnetic inclination error in sedimentary rocks: a comparative approach. Physics of the Earth and Planetary Interiors 152–165.

Torsvik, T.H., Trench, A., 1991. The Lower-Middle Ordovician of Scandanavia: southern Sweden re-visited. Physics of the Earth and Planetary Interiors 65, 283–291.

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 of London 158, 321–329.

Torsvik, T.H., Lohmann, K.C., Sturt, B.A., 1995. Vendian glaciations and their relation to dispersal of Rodinia: Paleomagnetic constraints. Geology 23, 727–730.

Torsvik, T.H., Eide, E.A., Meert, J.G., Smethurst, M.A., Walderhaug, H.J., 1998. The Oslo Rift: new paleomagnetic and isotopic constraints. Geophysical Journal International 135, 1045–1059.

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, paleogeography and dynamics. Earth-Science Reviews 114, 325–368.

Van der Voo, R., 1990. The reliability of paleomagnetic data. Tectonophysics 184, 1–9.

Van der Voo, R., Torsvik, T.H., 2004. The quality of the European Permo-Triassic paleopoles and its impact on Pangea reconstructions. In: Channell, J.E.T., Kent, D., Lowrie, W., Meert, J.G. (Eds.), Timescales of the Paleomagnetic Field, pp. 29–42.

Van der Voo, R., French, R.B., Williams, D.W., 1976. Paleomagnetism of the Wilberns Formation (Texas) and the Late Cambrian paleomagnetic field for North America. Journal of Geophysical Research-B 81, 5633–5638.

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.

Joseph Meert is a Professor of Geology in the Department of Geological Sciences at the University of Florida (Gainesville, Florida, USA). He is an associate Editor of *Gondwana Research*. He received his B.S. and M.S. from the University of Florida (1986, 1988); and his PhD from the University of Michigan (1993); worked as a Post-Doctoral Fellow (1994) at the University of Michigan and taught at Indiana State University (Terre Haute, Indiana) until 2001. Meert was a Fulbright Senior Scholar at the Norwegian Geological Survey (2000–2001; Trondheim, Norway) and a visiting Professor at the University of Paul Sabatier, France (2001). He has worked in Gondwana and peri-Gondwana regions (Kenya, Tanzania, Burundi, Namibia, Madagascar, India, Mongolia, Kazakhstan and Kyrgyzstan) since 1989 studying the assembly and breakup of Neoproterozoic supercontinents. Together with his students, the work is aimed at deciphering the interplay between tectonics, evolution and global climate. He has also worked on such diverse issues such as geodynamics, the character of the Earth's magnetic field and the formation of Terra Rossa soils.