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Paleogeography of Baltica in the Ediacaran: Paleomagnetic and geochronological data from the clastic Zigan Formation, South Urals

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ABSTRACT

The paleoposition of Baltica at the end of Neoproterozoic is of utmost importance for global paleogeography, but paleomagnetic data of Ediacaran age are very controversial. Neoproterozoic and Ediacaran clastic rocks are wide spread along the deformed eastern margin of Baltica. Paleomagnetic and geochronological studies were carried out at the several sections of the uppermost Zigan Formation of the Ediacaran Asha Series along with Paleozoic rocks from the same region. An ash bed interlayered in the upper part of the Asha series yields a zircon deposition age of 547.6 ± 3.8 Ma. With the aid of stepwise thermal demagnetization, a dual polarity high-temperature remanence was successfully isolated from red beds of the Zigan Fm, and its primary origin is indicated by the positive reversal test and regional consistency test. The overall mean direction of this remanence (declination $D^{\circ} = 107.7$ (287.7), inclination $I^{\circ} = -15.4$ (15.4), radius of confidence circle $\alpha_{95}{}^{\circ} = 4.8$, $N = 36$ sites) corresponds to a paleolatitude of $7.8^{\circ} \pm 2.5^{\circ}$, N or S. Geological data indicate that the study area was a part of the Baltic craton at least since the early Neoproterozoic, while paleomagnetic results on Paleozoic rocks from the westernmost zones of the Ural fold belt reveal not local and regional rotation with respect to Baltica. Also, several lines of evidence imply that the inclination shallowing in these rocks either absent altogether, or at worst less than 10°; hence the position of Baltica can be reliably reconstructed for time about 550 Ma. The analysis of the existing paleomagnetic and geological data place Baltica to the east of Laurentia in tropical southern latitudes with the Uralian margin facing north in Late Ediacaran time.

1. Introduction

A 300 Ma span of time from the middle Neoproterozoic through the Middle Cambrian (~800–500 Ma) heralded major developments such as the evolution of complex bauplans and bioturbation (Crimes, 1992; Signor and Lipps, 1992; Bowring and Erwin, 1998; Knoll, 2001; Babcock et al., 2001; McCall, 2006). This same time interval was also punctuated by severe glacial epochs (Roberts, 1976; Kirschvink, 1992; Meert and Van der Voo, 1994a,b; Hoffman et al., 1998; Evans, 2000); saw increased oxygen levels in the atmosphere and in the shallow and deep oceans (Canfield and Teske, 1996; Berner et al., 2003; Holland, 2006; Canfield et al., 2007); included many (and sometimes rapid) changes in continental configurations (Meert et al., 1993; Kirschvink et al., 1997; Evans, 1998; Meert, 1999; Meert and Tamrat, 2004; Maloof et al., 2006; Li et al., 2008) along with other enigmatic geological, biological, astronomical and geophysical events (Williams, 1975, 1986; Walter et al., 2000; Puffer, 2002; Kirschvink and Raub, 2003).

Many of these changes may be interrelated and connected (at least in part) to the distribution of continents across the globe. There have been numerous attempts to provide a robust Neoproterozoic paleogeography using paleomagnetic data, however; both data and reconstructions are controversial. The Ediacaran time period (~635–542 Ma) is a prime example of such a situation (McCausland et al., 2007; Meert et al., 2007; Meert, 1999, 2013; Kirschvink et al., 1997; Pisarevsky et al., 2008; Abrajevitch and Van der Voo, 2010; Schmidt and Williams, 2010). The problems are particularly acute for Laurentia and Baltica, where available paleomagnetic data lead to contrasting interpretations. These include high or low latitude positions of Laurentia and Baltica, rapid continental drift, rapid true polar wander, inertial interchange true polar wander and non-dipole fields depending on the perspective of the author (for examples see Meert et al., 2007; Pisarevsky et al., 2008; Abrajevitch and Van der Voo, 2010; Meert, 2013). The following is a brief review the Ediacaran paleomagnetic database of Baltica.

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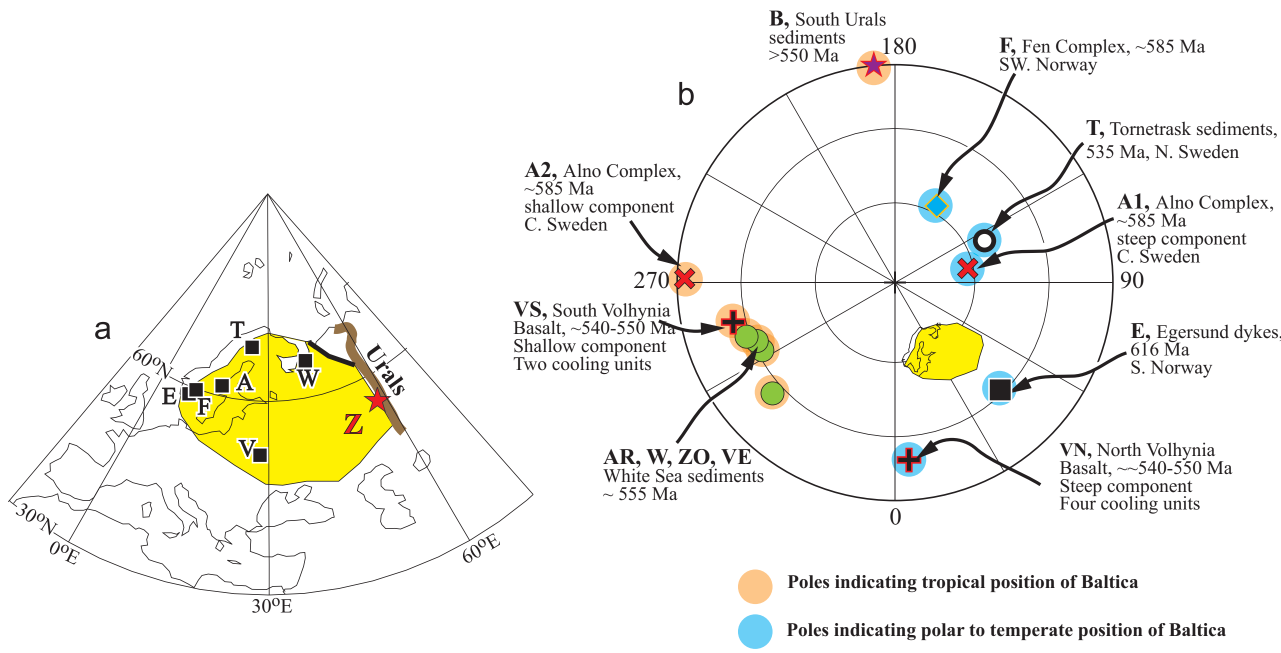

Fig. 1. (a) Location of the Baltica block with Precambrian basement (shaded), the Urals (brown band), the Timan Range (thick black line), previously sampled <650 Ma units (full squares) and the study area in the South Urals (Zigan formation, Z, red star), where Ediacaran sediments have been studied by Golovanova et al. (2011). (b) Stereoplot of Ediacaran and Early Cambrian paleomagnetic poles from Baltica projected onto the northern hemisphere. (A) A = Alnö Complex (Piper, 1981; Meert et al., 2007); E = Egersund dykes (Walderhaug et al., 2007); F = Fen Complex (Piper, 1988; Meert et al., 1998); V = Volhynia, Ukraine (Elming et al., 2007); W (poles A, W, VE, ZO) = White Sea region, Russia (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005); T = Tornetrask Formation (Torsvik and Rehnström, 2001) and (B) Ediacaran Basu Formation (Golovanova et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The sole Early Ediacaran pole comes from the Egersund dykes in SW Norway (E in Fig. 1a; Table 1; Walderhaug et al., 2007). This pole is reliably dated at 616 ± 3 Ma (zircon U-Pb age; Bingen et al., 1998), and its paleomagnetic quality is seemingly confirmed by a positive baked contact test. The pole places Baltica at intermediate to high paleolatitudes.

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; F and A, respectively, in Fig. 1a; Table 1). These carbonatite complexes are nearly coeval (~585 Ma), and their corresponding paleomagnetic data (Fig. 1b) can place the study locations in Baltica at intermediate latitudes (Fen pole, F), close to the geographic pole (Alnö steep component, A1) or in the tropics (Alnö shallow component, A2). Meert et al. (2007) rightly concluded that these data should be regarded with extreme care when attempting continental reconstructions (see also Meert, 2013).

In Volhynia (southwestern Baltica; V in Fig. 1a; Table 1), the Ediacaran section is comprised of a several hundred meters thick succession of lava flows and tuffs (known mostly from boreholes) that is overlain by a 200 m thick sedimentary cover. Relatively few U-Pb ages on zircons from the volcanic rocks yield a late Ediacaran-Fortunian age of ca. 550–540 Ma (Compston et al., 1995; Nosova et al., 2010), although older ages of ~580 Ma were inferred from $^{40}Ar/^{39}Ar$ data (Elming et al., 2007) that may suffer from an inherited Ar-component. Three teams independently studied paleomagnetism of these volcanics (Iosifidi et al., 2001; Nawrocki et al., 2004; Elming et al., 2007). The sampling was limited to two small

Table 1
Paleomagnetic North Poles from Baltica (Ediacaran–Early Cambrian).

Key	Location	Slat	Slong	Plat	Plong	Age	Δ	IA	Reference
T	Tornetrask Fm/N Sweden	68.2	19.5	55.9	115.5	535	<5	Tr-J (210)	Torsvik and Rehnström (2001)
Z	Zigan Fm/S. Urals	53.7	56.7	−16.2	138.4	~550[a]	~20		This paper
W	Winter Coast/N. Russia	65.5	39.8	−25.2	132.1	555	≫20		Popov et al. (2002)
AR	Arkhangelsk/N. Russia	65.6	40.5	−28.3	110.0	555	≫20		Iglesia Llanos et al. (2005)
ZO	Zolotitsa/N. Russia	65.5	40.0	−31.7	112.9	555	≫20		Popov et al. (2005)
VH	Verkhotina/N. Russia	64.8	40.5	−32.2	117.0	555	≫20		Popov et al. (2005)
VS	Volhynia South/W. Ukraine	50.9	26.4	−24.1	103.1	540–550	≫20		Elming et al. (2007)
	Mean 2–7/ZWV pole	–	–	−26.9	115.0				This paper
VN	Volhynia North/W. Ukraine	51.2	26.1	19.8	4.4	540–550	≫20		Elming et al. (2007)
B	Basu Fm/S. Urals	54	57	1.1	187.3	≥550[b]	<5	O-S (440)	Golovanova et al. (2011)
F	Fen Complex/S. Norway	59.3	9.3	56.7	151.2	583	<3	P (240)	Meert et al. (1998)
A1	Alnø steep/C. Sweden	62.5	17.5	62.7	101	584	~1	Tr-J (190)	Meert et al. (2007)
A2	Alnø shallow/C. Sweden	62.5	17.5	3.5	269	584	≫20		Meert et al. (2007)
E	Egersund Dikes/S. Norway	58.4	6.2	31.4	44.1	616	~11	Oe (480)	Walderhaug et al. (2007)

Notes: Slat, Site latitude (°N). Slong, Site longitude (°E). Plat, Paleomagnetic pole latitude (°N if positive). Plong, Paleomagnetic pole longitude (°E). Age, rock age: Age determination by pole (1) fossil correlation; (2) inferred; (3–7 and 9) U–Pb zircon; (11–13) $^{40}Ar/^{39}Ar$ biotite; (14) U–Pb zircon and $^{40}Ar/^{39}Ar$ biotite. Δ (°), Angular distance from the nearest point on the Phanerozoic APWP for Baltica (Torsvik and Cocks, 2005). IA, Age of the remanence inferred from this APWP, with the numerical age of the nearest referent pole: Tr-J, Late Triassic-Early Jurassic; P, Permian; O-S, Late Ordovician-Early Silurian; and Oe, Early Ordovician.

[a] See text for discussion of the age of the Zigan Fm in the South Urals.

[b] Indicated by our results from the Ust-Katav locality (see text for more details).

quarries with no more than four cooling units in the northern part of Volhynia and only one or two cooling units were sampled in two small quarries in the south. Elming et al. (2007) note that the "northern" sites (VN) indicate a high-paleolatitude position for Baltica, whereas the "southern" sites (VS) place central Baltica at a latitude of ~20° N or S. Iosifidi et al. (2005) published paleomagnetic data on the overlying Ediacaran (Vendian) sediments (Velikanov, 1985) in the same region and recognized six different remanent directions 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); however, we note that none of their directions infers a high-latitude position for Baltica during the Late Ediacaran–Early Cambrian.

Ediacaran-age rocks are known over a large region in northern Russia, but mostly in boreholes whereas outcrops are confined to a limited area on the southeastern coast of the White Sea (Winter Coast, W in Fig. 1a). The stratigraphic age of these rocks is confirmed by ~555 Ma U-Pb age on volcanic zircons from ash beds (Martin et al., 2000; Grazhdankin, 2003). Four reasonably consistent poles, all from a rather narrow stratigraphic interval, are available from this area (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005). All these poles all place Baltica at low latitudes.

Early to Late Cambrian poles from the Tornetrask-Dividal (~535 Ma) and Andarum limestones (~500 Ma) place central Baltica at intermediate paleolatitudes (Table 1; Torsvik and Rehnström, 2001). Lastly, well-constrained Ordovician poles from the St. Petersburg limestones (~478 Ma; Smethurst et al., 1998;Table 1) and Swedish Limestones (~458 Ma; Torsvik and Trench, 1991; Table 1) move central Baltica from high to intermediate southerly latitudes.

With regard to the Ediacaran drift history of Baltica, we are left with the following conundrum. Some Ediacaran poles (all W results, low-latitude A pole, low-latitude VS pole) imply that Baltica straddled the *tropics*, while the others (high-latitude A pole, high-latitude VN pole) favor a *high* latitude location (Fig. 1b) (further on referred to as low-latitude and high-latitude poles, respectively). In summary, the position of Baltica during the Ediacaran–Early Ordovician must begin and end at relatively high (and most probably) southerly latitudes, but there are no unequivocal data for placing Baltica at *any* latitude during the interval from ~585 to 500 Ma.

What is the potential for improving the paleomagnetic dataset for Baltica for the ca. 650–520 Ma interval? The Ediacaran volcanics of Volhynia were visited three times, and limited outcrop precludes obtaining any new data. The sedimentary rocks of Volhynia may deserve more attention, but given the complexity of the previous results, these rocks should not be viewed as a strong candidate for future work. Each of carbonatite complexes (Fen and Alnö) in Scandinavia were studied at least twice along with the limited outcrop of the coeval "rödberg" sediments (Poorter, 1972; Piper, 1981, 1988; Meert et al., 1998, 2007). The results of those studies are equivocal in that the Fen Complex resides near the Permo-Triassic Oslo rift and has a paleomagnetic pole that differs only slightly from Permo-Triassic directions and the coeval Alno Complex of Sweden yielded a complex distribution of directions none of which match the Fen pole (Meert, 2013). We feel there is little to be learned from a re-examination of these locations. The Ediacaran sediments of the White Sea coast were studied extensively (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005) and yielded self-consistent directions. It is unlikely that any additional paleomagnetic studies will yield new information. Late Precambrian sediments of the Timan Range along the northeastern boundary of Baltica (Fig. 1a) are strongly metamorphosed and therefore poor candidates for a paleomagnetic study.

Although the list of Ediacaran targets on cratonic Baltica appears exhausted, there is a nearly 1000-km-long band of Neoproterozoic and Ediacaran rocks in the western part of the South and Middle Urals along the Baltican margin (Figs. 1a and 2a). In particular, a nearly 1800 m thick Ediacaran terrigenous sequence is located in the South Urals (Keller and Chumakov, 1983; Bekker, 1988). These para-autochthonous units offer an opportunity to resolve the ongoing controversy regarding the late Cryogenian–Ediacaran–Early Cambrian position of Baltica. In order to convincingly solve this major controversy; however, one must, *first*, reliably date these rocks; *second*, obtain demonstrably reliable paleomagnetic results from Ediacaran rocks; and *third*, precisely evaluate subsequent motion of study areas with respect to the craton.

As part of an effort toward resolving some of the controversies inherent in the Baltica paleomagnetic database, we undertook an investigation of Ediacaran rocks from the Ural fold belt both for paleomagnetism and geochronology.

It is possible to utilize geological and tectonic information to evaluate the coherence of cratonic Baltica with our localities in the Uralian fold belt. Local (and or regional) rotations can also be evaluated via comparison of coeval paleomagnetic data from the same areas with those from cratonic Baltica. For example, early paleomagnetic studies in the Urals showed a magnetic remanence with a moderately steep negative inclination and SW declination is commonly observed in Paleozoic and Precambrian rocks that agrees very well with Permian reference directions for Baltica (Khramov et al., 1973; Danukalov et al., 1982; Shipunov, 1997, 1998; Svyazhina et al., 2003). Deformation of the westernmost tectonic units of the Ural fold belt took place during mid-Permian (Kungurian) time (Puchkov, 2003). This late Paleozoic remanence is a useful tool for evaluating the magnitude of tectonic rotations between these units and Baltica *sensu stricto* and also to ascertain whether or not the Ediacaran data from the western Urals can be extrapolated over the entire craton. The available late Paleozoic data, however, are spread over the nearly 400 km wide Ural fold belt, and a more "concentrated" view at its westernmost part is desirable. Hence a study directed toward isolation of these younger remanences was carried out and presented herein.

2. Geological setting

At a very general scale, the easternmost tectonic units of the Ural fold belt are thought to be allochthonous with respect to Baltica and to have docked with Baltica during the Devonian or even later (Puchkov, 2003; Brown et al., 2006). In contrast, the western parts of the Uralian fold belt are remarkably similar to those of cratonic Baltica. In particular, a more than ten kilometers thick succession of Meso- and Neoproterozoic sedimentary rocks is exposed in the Bashkir anticlinorium (Uplift) in the western South Urals (Fig. 2a). This succession is reliably correlated with section from boreholes in the Ural Foredeep and to the eastern parts of Baltica and further supported by a series of seismic profiles (Keller and Chumakov, 1983). Although eastward-dipping seismic boundaries under the Bashkir Uplift are interpreted as the consequence of westward thrusting of the Uralian units over the craton (Puchkov et al., 2001), the magnitude of this thrusting is not considered to be significant, and the study area was still part of the Baltica deformed margin since the early Neoproterozoic (~1 Ga; Puchkov, 2003).

Exposed within the Bashkir Uplift is a nearly ten kilometer thick succession of Meso- and Neoproterozoic age clastic sediments and carbonates with subordinate Mesoproterozoic volcanics (Keller and Chumakov, 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,

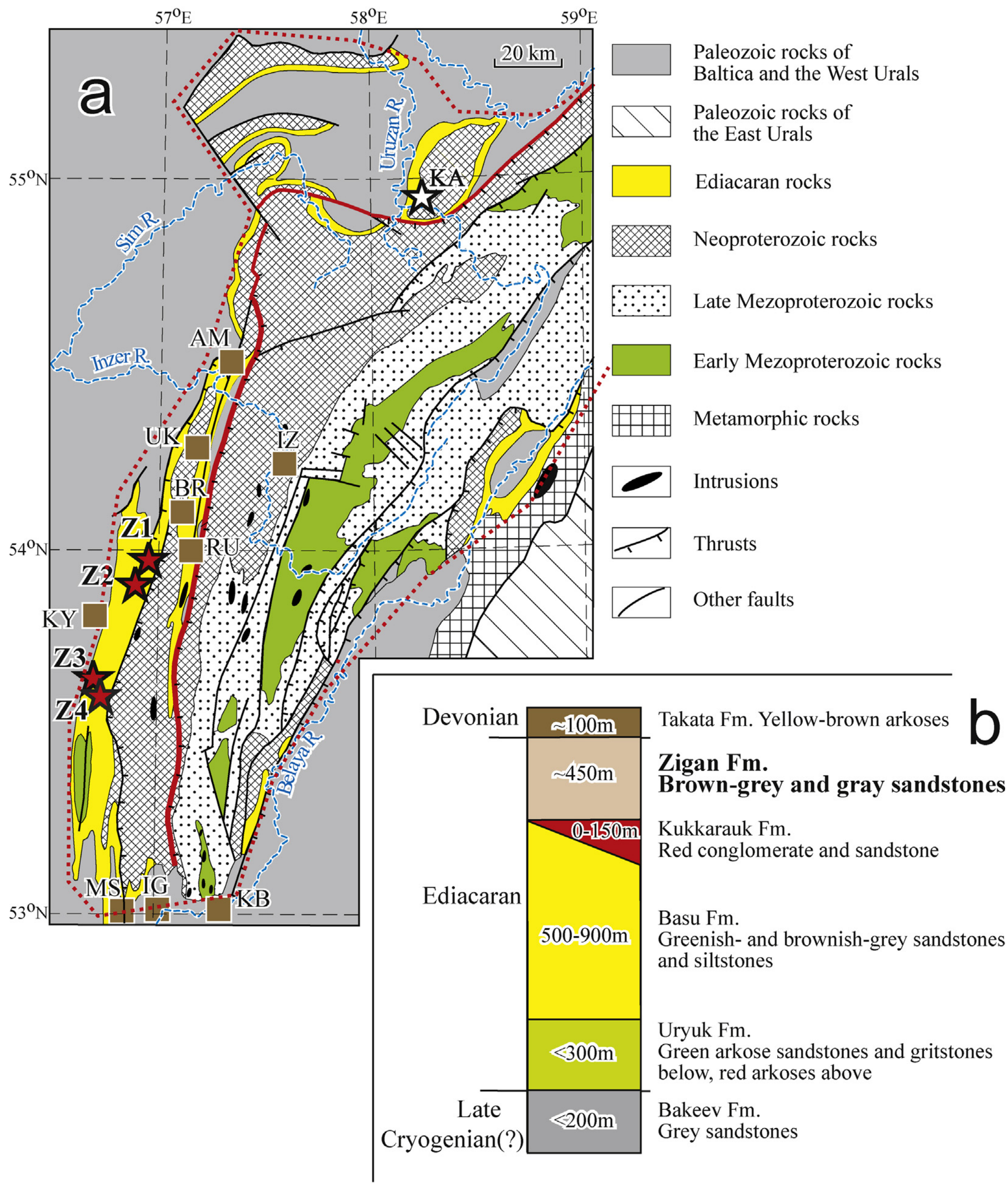

Fig. 2. (a) Schematic map of the SW Urals with the limits of the Bashkir Anticlinorium shown as thick dotted line (simplified after Kozlov, 2002). The thickest red line denotes the Zilmerdak Fault, to the west of which Ediacaran rocks are overlain by Paleozoic rocks without angular unconformity. Red stars denote the localities numbered as in the text and Table 1, where the Upper Ediacaran Zigan Formation was sampled. White star is the Ust-Katav locality where ash bed among the undifferentiated upper Asha Series was sampled for geochronology. Brown squares are the localities where late Paleozoic overprint components were isolated from Paleozoic and Precambrian rocks; overprint data are labeled as in Table 3. (b) Simplified stratigraphic column of the Ediacaran sequence of the SW Urals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

the Bakeev, Uryuk, Basu, Kuk-Karauk and Zigan Formations in ascending order (Fig. 2b). 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. The sections vary laterally; this and limited patchy exposures along river beds and roads lead to a situation that two sections of the same formation a few kilometers apart on the opposite limbs of a fold cannot be matched precisely.

The uppermost member of the Series, the Zigan Fm., comprises up to 450 m, usually ~300 m, of greenish-gray and brown-gray, sometimes maroon, sandstone with subordinate siltstone. The Basu and Zigan Formations are very similar lithologically and can be reliably discriminated only in the sections where the rocks of Kuk-Karauk separates them.

The Kuk-Karauk Formation is presented mostly by the coarse-grained red sandstones. In the middle of the Kuk-Karauk section there is a layer of red polimictic conglomerates. These Kuk-Karauk Conglomerates is the only regional marker horizon which separates the Basu and Zigan Formations. This horizon 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.

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. 2a), 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 clastics paraconformably (and locally unconformably) overlie earlier Neoproterozoic rocks and are in turn paraconformably 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 underlying members of the Asha Series, the Kuk-Karauk Conglomerate and Basu Fm. (Kuznetsov et al., 2012a,b) 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. Also, 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). Thus the age of the Basu Fm. is in the 560–575 Ma interval.

3. Sampling localities

The sampling localities of the Zigan Formation used in this study are shown in Fig. 2a (Z1 to Z4). All samples were collected as oriented hand specimens and later cut into cubes for paleomagnetic analysis. At locality Z1 (53.97° N, 56.89° E), an ~30 m thick continuous exposure of interlayered red, brown and greenish-gray sandstones from the lower Zigan Fm. was sampled from a road cut along with several isolated outcrops of greenish-gray sandstone from the middle and upper part of the formation. In total, 66 samples were taken. At locality Z2 (53.91° N, 56.82° E), several isolated outcrops of greenish-gray sandstone were studied along the Mendym riverbed where 42 samples were taken. At locality Z3 (53.56° N, 56.66° E), 125 samples were collected from an ~60 m thick nearly continuous exposure of brown-gray sandstones from the lower Zigan Fm. along with a few isolated outcrops of greenish-gray sandstone from the middle and upper part of the same formation were sampled along the banks of the Zigan river. Finally, at locality Z4 (53.57° N, 56.68° E), the formation is fully exposed (with the exception of the lowermost ~40 m) in a deep road cut where 127 samples were taken from an ~80 m interval of brown to red sandstones in the lower half of the formation. Two beds of mudstone interpreted as ash beds were found interlayered in the brown-colored rocks, and one more ash bed was located at the very top of the Zigan section, just about 1 m below the conformable contact with Early Devonian sandstone. All three ash beds were collected for U-Pb zircon studies.

Recently, Grazhdankin et al. (2011) found five thin (3–7 cm) ash beds in the northern part of the Bashkir Uplift (Ust-Katav locality in Table 3; 54.94° N, 58.17° E). The upper part of the Asha Series in this area does not contain the Kuk-Karauk Conglomerate marker horizon that definitively separates the lithologically similar Basu and Zigan Fms. A sample of the ash bed was collected here. This sample can be attributed to any of the Basu or Zigan Formation.

We note that no angular unconformity exists between the Ediacaran to mid-Permian sedimentary sequences to the west of the Zilmerdak Fault and that all the folding and thrust faulting in the region is of mid-Permian age (Puchkov, 2003). Given this deformational history it is most likely that any local rotations are also of this same age; yet we note the overall lack of any structural evidence for any rotations within the conformable sections. In order to test this with the aid of paleomagnetic data, we sampled various Paleozoic rocks, mostly carbonates, from a number of localities from the western rim of the Bashkir anticlinorium (Fig. 2a). Usually, 10–20 hand-samples were taken from each monoclinal section.

4. Geochronology

4.1. Methods

All samples of presumed ash bed are non-indurated mudstone that easily disintegrated in water. The samples were then rinsed using an anionic surfactant (like Calgon) followed by water table treatment with very slow sample feed rates. This was followed by heavy liquid (TBE and MEI) mineral separation with multiple agitation periods. The sample was repeatedly passed through a Frantz isodynamic magnetic separator using a current of 1.0 A with 2–4° tilt. Finally, transparent euhedral to nearly anhedral zircon grains were handpicked from the least magnetic fraction under an optical microscope to ensure the selection of the clearest grains only. The zircons were mounted in resin and polished to expose median sections. The mount was cleaned in 5% nitric acid (HNO_3) to remove common-Pb surface contamination. The polished zircons were imaged with both plane light using the optical microscope and the cathodoluminescence detector using the scanning electron microscope to guide analysis.

U-Pb isotopic analyses were conducted at the Department of Geological Sciences (University of Florida) on a Nu Plasma multi-collector plasma source mass spectrometer equipped with three ion counters and 12 Faraday detectors. The LA-ICP-MS is equipped with a specially designed collector block for simultaneous acquisition of ^{204}Pb (^{204}Hg), ^{206}Pb and ^{207}Pb signals on the ion-counting detectors and ^{235}U and ^{238}U on the Faraday detectors (see Simonetti et al., 2005). Selected zircon grains were ablated using a New-Wave 213 nm ultraviolet laser. During U-Pb analyses, the sample was decrepitated in a He stream and then mixed with Ar-gas for induction into the mass spectrometer. Background measurements were performed before each analysis for blank correction and contributions from ^{204}Hg. Each sample was ablated for ~30 s in an effort to minimize pit depth and fractionation. Data calibration and drift corrections were conducted using the FC-1 Duluth Gabbro zircon standard. Data reduction and correction were conducted using a combination of in-house software and Isoplot (Ludwig, 1999). Average ^{204}Pb counts were calculated for the Duluth gabbro standards as well as each sample. Samples that yielded ^{204}Pb counts above the mean for the Duluth gabbro were rejected from the analysis. Representative age errors based on the long-term reproducibility of FC-1 were 2% for ^{206}Pb/^{238}U (2σ) and 1% for ^{207}Pb/^{206}Pb (2σ). Additional details can be found in Mueller et al. (2008) and Pradhan et al. (2012).

4.2. Results

Although we obtained a reasonable yield of zircons from three "ash" samples at locality Z4, the analyses yielded a wide range of ages indicating that perhaps the 'ash' samples were reworked sedimentary rocks and ash. Results from these samples are reported in Kuznetsov et al. (2012a,b). In contrast, more relevant data were obtained from an ash sample from locality KA in the northern part of the Bashkir Uplift (Fig. 2a). A total of 51 LA-ICP-MS analyses were collected in from 51 individual zircon crystals. In a Tera–Wasserberg diagram (Fig. 3a), we plot all of the 51 analyses and note that most define a coherent ^{206}Pb/^{238}U cluster with some scatter in ^{207}Pb/^{235}U values and variable mainly normal discordance. The average ^{206}Pb/^{238}U age of 547.6 ± 3.8 Ma (MSWD = 1.4) for 47/51 analyses is regarded as the best age for deposition of the ash layer and is used in the discussion below (Fig. 3b). The four

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

Data	AzD°	Dip°	*n*	In situ				Tilt-corrected			
				D°	*I*°	*k*	α_{95}°	*D*°	*I*°	*k*	α_{95}°
Loc. Z1											
P1167-A	289	24	8/7	107.7	−42.6	34	10.6	108.1	−18.6	28	11.6
P1161-CA	293	22	6/6	279.1	33.3	8	25.7	281.1	12.1	8	24.9
P1155-C	306	20	8/3	290.1	42.6	7	50.8	293.3	23.3	9	43.1
P1155-A	304	23	8/3	106.9	−44.0	12	37.5	110.8	−22.2	10	40.9
P1147-CA	286	18	8/3	255.4	32.5	7	49.2	260.5	17.2	7	50.6
Loc. Z3											
N5093-C	266	25	8/4	287.4	23.7	19	21.9	285.5	0.1	18	22.5
P1209-A	282	29	7/2	89.4	−44.4	–	–	92.7	−15.9	–	–
N5085-CA	278	24	8/4	268.1	40.8	7	39.2	270.3	16.8	7	37
N5077-AC	286	26	8/7	116.7	−47.2	10	20.6	113.6	−21.4	8	22.2
M1695-A	278	26	7/6	125.8	−39.7	29	13	119.8	−15.7	24	14.2
P1195-C	277	25	7/5	308.5	38.1	35	14.1	302.3	15.9	35	14.1
N5069-C	276	28	8/6	301.2	29.7	10	22.2	297.8	4.4	9	23.9
M1688-C	282	29	7/7	284.7	46.3	45	9.1	284	17.8	94	6.2
M1681-C	307	27	7/3	298.0	22.5	16	32.3	298.6	−4.6	13	35.9
M1681-A	283	30	7/3	121.5	−34.5	111	19.5	118.3	−5.4	283	12.2
P1187-CA	280	27	8/8	297.5	42.6	15	14.9	293.3	17.1	14	15.4
M1674-A	291	23	7/6	91.1	−44.3	50	9.5	95.8	−22.3	42	10.5
P1180-C	294	27	7/3	283.7	40.8	240	9.4	285.9	13.9	199	10.3
N5061-C	278	24	8/7	308.6	2.2	4	33.1	310.4	−18.6	5	32.2
Loc. Z4											
C114-C	292	24	7/3	271.1	48.0	22	27.1	276.7	25.5	25	25.3
C114-A	299	26	7/3	118.0	−39.1	66	15.3	118.2	−12.7	87	13.3
N5241-C	298	21	7/3	243.0	48.8	19	29.5	257.2	34.2	23	26.1
N5241-A	279	21	7/4	100.4	−42.6	11	29	100.1	−21.4	13	26.6
N5257-C	282	23	7/6	281.7	19.8	23	14.5	281.8	−3.6	20	15.6
N5264-C	290	26	7/7	266.2	40.9	74	7.1	271.5	16.8	51	8.5
N5271-C	287	23	8/8	283.2	36.0	27	10.9	283.8	13.3	24	11.6
C121-C	289	23	5/4	292.4	48.8	14	25.8	291.6	25.8	15	24.3
P1330-C	292	21	6/6	272.9	39.6	33	11.9	276.5	19.1	36	11.3
P1323-C	291	23	7/4	260.0	30.4	28	17.7	264.1	10.1	39	15
P1316-C	283	20	7/4	298.0	23.3	18	22.2	296.8	4.0	16	23.6
P1316-A	287	23	7/3	114.4	−47.2	72	14.6	112.5	−24.3	63	15.7
P1309-A	290	24	7/6	103.8	−36.8	9	24.1	105.0	−12.8	8	25.3
M1838-C	288	24	10/4	298.2	54.9	11	29.1	294.7	31.5	13	26.8
M1838-A	287	23	10/4	95.7	−41.4	19	21.6	98.1	−18.6	23	19.6
M1830-A	307	28	8/5	79.1	−37.4	25	16.1	89.0	−17.0	25	16.1
M1821-A	280	29	9/6	136.6	−49.0	16	17.1	125.5	−23.9	14	18.3
All A			(14)	107.4	−43.1	44	6.1	107.7	−18.3	47	5.9
All C			(22)	284.2	36.8	20	7.1	284.9	13.6	20	7.1
All			(36)	285.4	39.3	25	4.9	286.0	15.4	26	4.8
All[a]			(25)	286.8	38.2	24	6.0	286.6	14.4	28	5.6
								Plong	Plat	*k*	A_{95}
Pole			(36)					138.1	16.3	36	4.1

Comments: Localities are labeled as in Fig. 2a. Sites are labeled by a capital character with numerals (C114, P1316, etc.). If all samples are in a site of the same polarity, site-name is succeeded by A and C for northwestern and southeastern directions, respectively. If both polarities are present but one is met in one or two samples only, one mean is given with both characters in its label. Finally, if both polarities are present in three or more samples each, the site is divided into two sub-sites with the same name but different polarity labels (e.g., M1838-C and M1838-A). AzD and Dip, azimuth of dip and dip angle. *n*, number of samples (sites) studied/used. *D*, declination. *I*, inclination. *k*, concentration parameter. α_{95}, radius of 95% confidence circle (Fisher, 1953). For Pole: Plong, pole longitude. Plat, pole latitude. *k*, concentration parameter. A_{95}, radius of 95% confidence circle.

[a] Sites based on > 3 samples only.

remaining analyses are statistically older with a $^{206}Pb/^{238}U$ age above 580 Ma (analyses 6, 11, 12, 31 in Table S1). These analyses probably carry some inheritance.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.06.006.

It should be repeated that the studied tuff sample is from the Ust-Katav locality, where the Basu and Zigan Fms are not separated by the Kuk-Karauk Conglomerate marker horizon. Thus, it is unclear whether this age corresponds to the Basu or to the Zigan Formation. However, according to the reported list of the Ediacaran fossils (Bekker, 1992, 1996), the clastics of the Basu Fm. must have been accumulated within the 560–575 Ma interval. Thus, the mean age of 547.6 ± 3.8 Ma most probably corresponds to the Zigan Fm.

5. Paleomagnetism

5.1. Methods

Paleomagnetic samples were collected as hand-sized blocks oriented with a magnetic compass. A set of samples collected from a distinct, and ∼ few meters thick section is considered a site. Every seven to ten consecutive samples within a continuous section were also regarded as a single site.

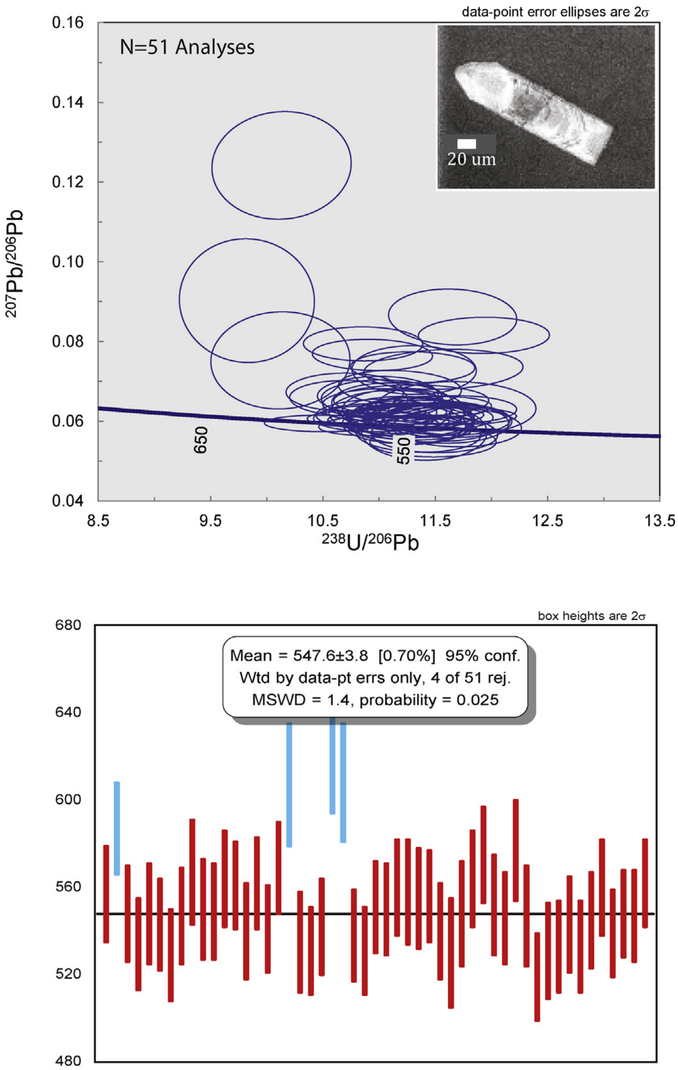

Fig. 3. (a) Tera–Wasserberg diagram showing all 51 zircon analyses from the Zigan Formation (Table 2) inset shows a CL image of a euhedral zircon from that population and (b) weighted mean $^{206}Pb/^{238}U$ age of 547.6 ± 3.8 Ma based on 47/51 individual zircon analyses (2σ; Table S1). Rejected samples shown in blue color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

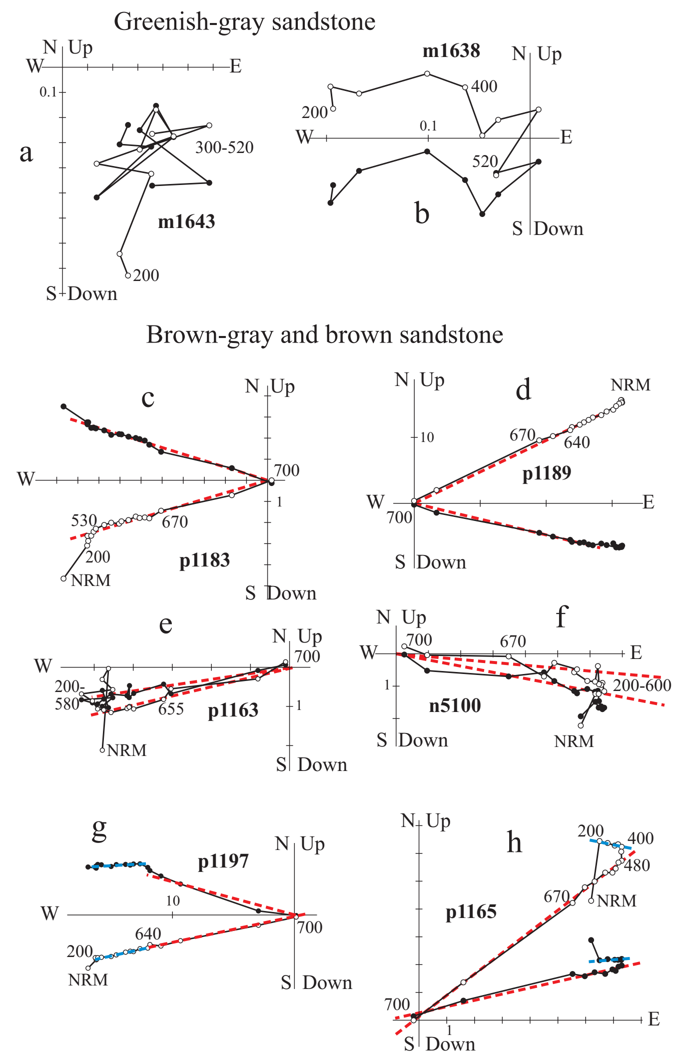

Fig. 4. Representative thermal demagnetization plots of greenish-gray (a and b) and brown-gray and maroon (c and h) varieties of the Ediacaran Zigan Formation from the western part of the South Urals, in stratigraphic coordinates. Isolated intermediate- (blue) and high-temperature (red) components are 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The collection was studied in the Paleomagnetic laboratories of Geological Institute of the Russian Academy of Sciences in Moscow and of Institute of Geology of the Uralian Branch of the Russian Academy of Sciences in the Ufa City. Cubic specimens of 8-cm^3 volume were cut from each hand sample. Individual specimens were stepwise heated in 12–20 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 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. If complete component separation is not achieved during demagnetization, we combined the PCA-calculated sample directions (Kirschvink, 1980) and remagnetization circles employing the technique of McFadden and McElhinny (1990). Paleomagnetic software written by Cogné (2003) was used in the analysis.

5.2. Results from the Zigan Formation

A single component of variable magnitude was removed from all rock varieties by heating to 200 °C or 250 °C. The overall mean in situ direction of this component (declination $D = 28.3°$, inclination $I = 68.3°$, radius of confidence circle $\alpha_{95}° = 6.7$, $N = 42$ sites) is close to the directions of both reference geomagnetic field ($D = 12.3°$, $I = 71.4°$) and dipole field ($D = 0°$, $I = 69.8°$) and is therefore most likely of recent (viscous?) origin.

Above 200 °C, nearly all greenish-gray samples show erratic behavior (Fig. 4a and b). In contrast, brown-gray and maroon varieties usually reveal a single high-temperature component (HTC) that decays to the origin by 650–700 °C, implying hematite as the main carrier (Fig. 4c–h). Sometimes, this main component is preceded by a weak intermediate-temperature remanence (Fig. 4g and

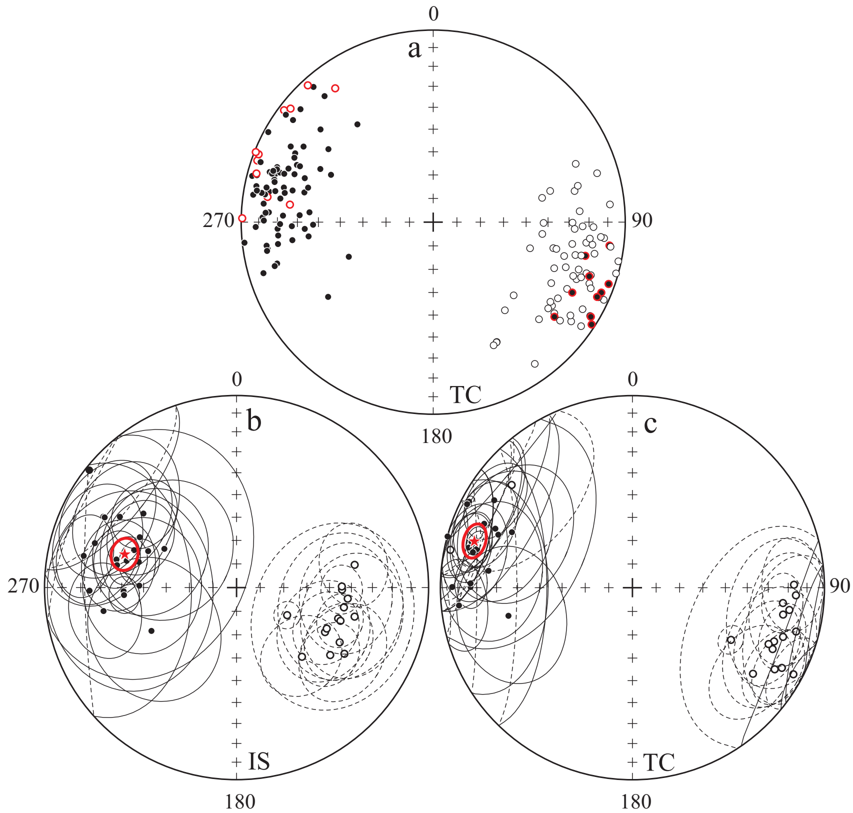

Fig. 5. Stereoplots of high-temperature component, HTC, in the late Ediacaran clastic rocks of the Zigan Fm. (a) Sample HTC data (circles) after tilt correction. In each polarity group, directions with inclination that differs from that of main body of the data are highlighted. (b and c) Site and sub-site mean directions (circles) with associated confidence circles (thin lines) in situ (b) and after tilt correction (c). Stars are overall mean directions with associated confidence circles (thick lines). Full (open) symbols and solid (dashed and dotted) lines are projected onto lower (upper) hemisphere.

h) with nearly chaotic directions. It may result from an unblocking spectrum that is a mixture of the present-day overprint and HTC.

The HTC vectors display antipodal directions on the stereonet that correspond to two polarities (Fig. 5a). Due to inherent ambiguity in the polarity options (normal or reverse) we label one set "PO1" (polarity option 1; Plat = 16° N, Plong = 318° E) and the other is labeled "PO2" (polarity option 2; Plat = 16° S, Plong = 138° E) (Fig. 6a). The angle $\gamma = 5.9°$ between mean directions for two groups of 83 "PO1" and 72 "PO2" vectors is less than the critical angle $\gamma_{crit} = 6.4°$. Therefore, the reversal test on the sample level is positive (class B) (McFadden and McElhinny, 1990).

It is common practice to present paleomagnetic results as a set of site-mean directions with associated statistical parameters along with an overall mean direction compiled from those sites. The reversal test is usually performed at the site-mean level. Interestingly, such a statistical approach is not straightforward in this study as often both polarities are present at a single site in the samples from different stratigraphic levels (magnetostratigraphy of the Zigan rocks will be described in more detail elsewhere). On one hand, combining directions of different polarity at the within-site level disguises the inherent difference between "C" and "A" directions; on the other, giving the equal weights to, for instance, a single sample direction and the mean of several data of opposite polarity from the same site is problematic. The following palliative is adopted. If one polarity includes just one or two samples from a site, such data are inverted, and the site-mean is ascribed to the dominant polarity. If each polarity group in a site includes three unit vectors or more, the site is divided into two sub-sites, and two means are used for further analysis (Table 2). Inevitably, α_{95} values of such sites may be large due to the small number of samples used to calculate the mean direction.

The compiled set of 37 mean directions (Table 2) is distributed similarly to that observed in the unit vectors (Fig. 5b and c). The angle $\gamma = 7.1°$ between the mean directions for 22 "C" and 15 "A" vectors is less than the critical angle $\gamma_{crit} = 9.8°$. Therefore, the reversal test at the site level is positive (class B; McFadden and McElhinny, 1990). The fold test is inconclusive due to the fact that there was limited variation in bedding attitudes (Table 2).

The positive reversal test is often regarded as strong evidence in favor of primary origin of a remanence; this conclusion, however, can be further substantiated. First, the overall mean paleomagnetic pole for the Zigan data falls at 16.2° N, 318.4° E, (16.2° S, 138.4° E) $A_{95} = 4.6°$ and differs by nearly 20° from the nearest Phanerozoic reference pole for Baltica (Fig. 6a). Therefore, it is considered unlikely that the Zigan remanence is the result of a younger remagnetization. Second, the Zigan pole does fall near several other Late Ediacaran poles from the White Sea region (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005) despite the ~1600 km distance between this region and the South Urals. Together, this regional consistency, the positive reversal test and the lack of similarity between the Zigan pole and all reference poles for Baltica constitute strong evidence of primary origin of the remanence in the Zigan Fm.

5.3. Late Paleozoic overprints in Paleozoic and Neoproterozoic rocks

In an effort to test for possible rotations between the westernmost part of the Urals and cratonic Baltica, a collection of Paleozoic and Neoproterozoic carbonates and clastic sediments from several localities (Fig. 2a) was studied. In more than half of the samples collected, we observed only an unstable (and most probably viscous) component of magnetization that was destroyed by 200–250 °C

Table 3
Late Paleozoic overprint directions in Paleozoic and Precambrian rocks.

Loc.	Age	Slat	Slon	AzD°	Dip°	*n*	In situ				Tilt-corrected			
							D	*I*	*k*	A_{95}	*D*	*I*	*k*	A_{95}
AM	D	54.6	57.3	95.3	30.8	13/6	197.6	−63.1	19	15.9	235.9	−45.8	12	20.1
IG	D	53.0	57.0	109.4	33.9	10/6	203.1	−41.5	24	13.9	228.1	−31.5	19	15.6
KY-1	D	53.7	56.7	287.0	32.1	11/7	249.9	−23.0	37	10.1	233.7	−46.1	35	10.4
KY-2[a]	D	53.7	56.7	94.0	44.0	2/2	234.8	−32.2	–	–	241.6	4.2	–	–
MS	S	53.0	56.9	83.3	35.9	12/9	203.7	−69.5	24	10.7	239.7	−40.9	31	9.4
KB-1	O	53.0	57.3	126.1	10.9	18/13	219.8	−42.7	38	6.8	229.6	−41.1	36	7.0
KB-2	O	53.0	57.3	74.4	25.1	9/5	232.5	−22.5	28	14.6	234.2	1.0	44	11.7
RU	E	54.0	57.2	100.7	47.4	[12/6]	222.2	−57.5	29	12.7	251.3	−21.3	29	12.7
UK	NP	54.3	57.2	292.2	25.4	7/5	249.6	−28.2	20	17.3	234.9	−44.8	16	19.5
IZ	NP	54.2	57.6	317.8	50.5	8/6	239.3	−46.2	34	11.6	193.1	−34.4	53	9.3
BR	NP	54.1	57.1	98.5	50.4	14/14	182.8	−46.2	38	6.6	225.2	−30.9	38	6.5
Mean[b]						[10]	223.9	−46.4	13	14.0	230.8	−34.8	18	11.5
60%[b]						[10]	229.3	−40.5	27	9.5				

Localities are labeled as in Fig. 2a. 60% is the overall mean upon 60% proportional unfolding. Age, age of rocks studied: NP, Neoproterozoic; E, Ediacaran, O, Ordovician; S, Silurian; and D, Devonian.
Other notation as in Table 3.

[a] Excluded from computation of the overall mean.

[b] Overall mean directions are computed by recalculating site-means to a common point at 54° N, 57° E.

(Fig. 7a–d). In other samples, there was a well-defined component isolated between 200 °C and 500 °C (Fig. 7a–d; Table 3). The overall tilt-corrected mean for this direction is Dec = 231, Inc = −36 (k = 20, A_{95} = 10.6°). These SW-Up site-means are better grouped in stratigraphic coordinates (Fig. 8a and b). Upon stepwise unfolding, the best data grouping is reached at 60% unfolding, although the difference between the maximum and tilt-corrected values of the precision parameter (k) is not "convincingly" significant (Fig. 8c and d). Tentatively, we conclude that, on the whole, the reverse remanence in Paleozoic and Neoproterozoic rocks can be regarded as synfolding.

No component with SW-Up directions was isolated from the Zigan rocks. In contrast, a directionally similar remanence was isolated from several pilot collections of Ediacaran and Neoproterozoic rocks in the western South Urals, from both carbonates (Fig. 7e) and clastics (Fig. 7f). This component is likely a late Paleozoic overprint too (Khramov et al., 1973; Danukalov et al., 1982; Shipunov, 1998), and Paleozoic and Neoproterozoic data can be pooled for this SW-Up component that well agrees with the Early Permian reference directions for Baltica (Fig. 8e).

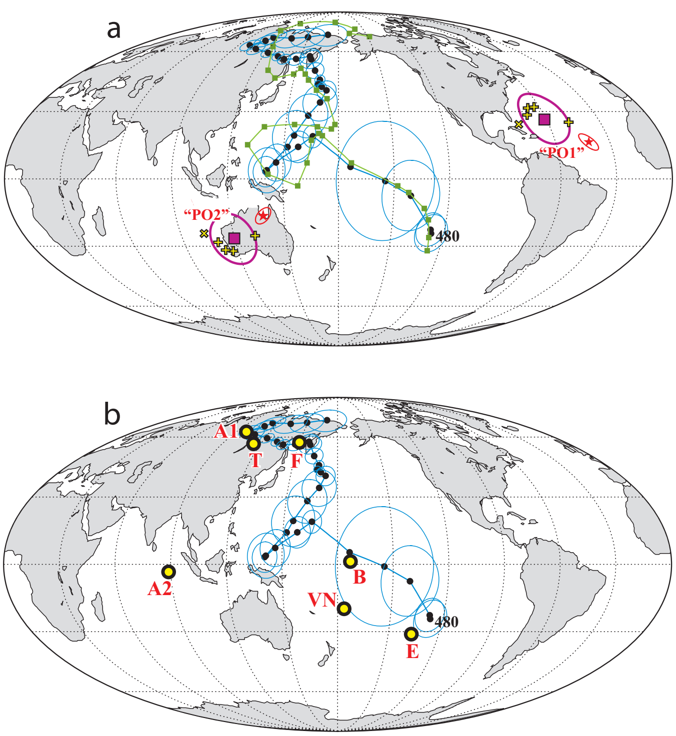

Fig. 6. (a) Two Phanerozoic APWP's for Baltica (dots, Torsvik and Cocks, 2005; squares, Smethurst et al., 1998; north poles are shown) and Late Vendian paleomagnetic poles from eastern Baltica (ZWV data): crosses, White Sea region (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005); oblique cross, south Volhynia (VS) pole (Elming et al., 2007); star with confidence oval, this paper. Big square is the overall mean of the ZWV poles with confidence oval (thick line) 480 is the Early Ordovician mean pole for Baltica (Torsvik and Cocks, 2005). (b) The APWP for Baltica (Torsvik and Cocks, 2005) and the "other" Ediacaran poles from Baltica (filled circles) keyed as in Fig. 1 and Table 1. For clarity, confidence circle is shown for the VN pole only (thin dashed line).

5.4. Coherence of the WESTERN South Urals and cratonic Baltica

Can we extrapolate the paleomagnetic data from the western South Urals to Baltica? The answer to this question requires evidence that the sampled region was not part of some far traveled terrane that was docked with Baltica during the Late Paleozoic. In part, we note initially that the Neoproterozoic sequences (~900–542 Ma) are reliably traced from the fold belt to the platform (Keller and Chumakov, 1983; Maslov, 2004; Kuznetsov et al., 2010). Secondly, despite the gaps in geologic record, no angular unconformities are found between the base of Ediacaran succession through the Middle-Late Paleozoic section until the mid-Permian in the westernmost units of the South Urals (Puchkov, 2003). Thus, there are no traces of collisional events within the stratigraphic package. Collectively, these observations make a strong case that the western tectonic units of the Urals are part of the deformed margin of cratonic Baltica and can be considered (at worst) para-autochthonous to cratonic Baltica (Puchkov, 2003; Maslov, 2004; Bogdanova et al., 2008).

While the section 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 we compared the overprint overall mean (Table 3) with the reference directions recalculated from the apparent polar wander path (APWP) of Baltica to a common reference location at 54° N, 57° E and found their very good agreement for the interval from 300 to 270 Ma (Fig. 8e). As the 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. Thus, both geologic and paleomagnetic data do not reveal significant

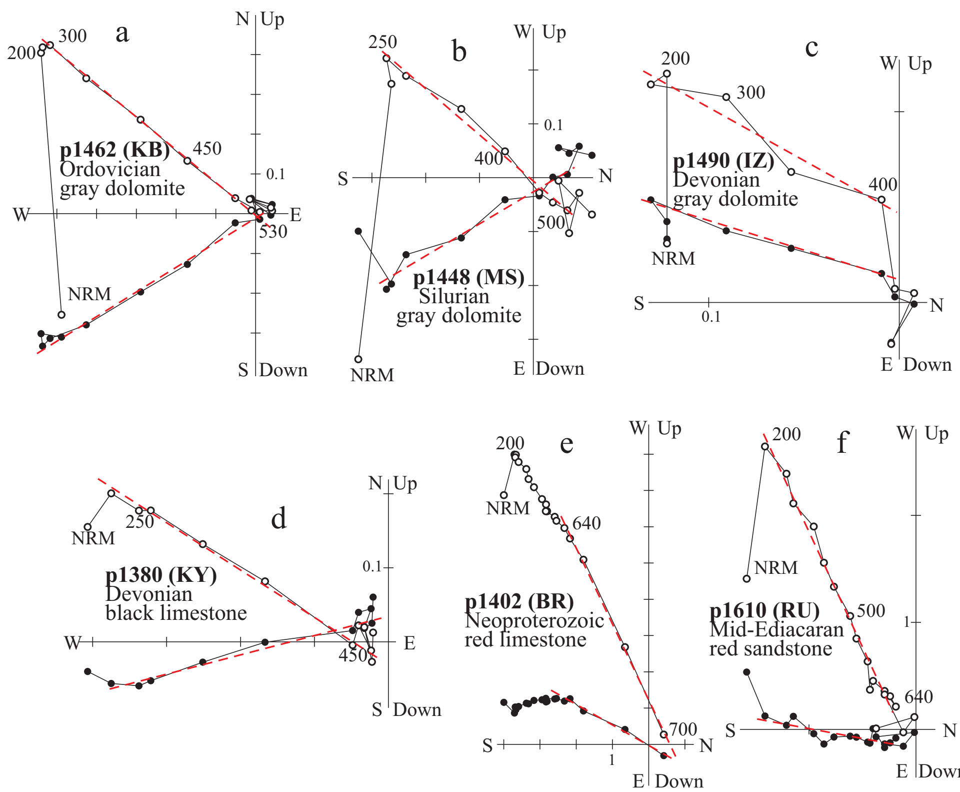

Fig. 7. Representative thermal demagnetization plots of Paleozoic (a–d) and Neoproterozoic (e–h) rocks from the western part of the South Urals, in geographic coordinates. Sample numbers are followed by locality names keyed as in Fig. 2a and Table 2. Reverse southwestern component is denoted by thick dashed lines. Other notation as in Fig. 4.

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 Cryogenian–Ediacaran interval.

6. Inclination shallowing?

The HTC mean inclination of $15.4° \pm 4.8°$ in the Zigan rocks points to a near-equatorial location of Baltica that is in accord with the Winter Coast results (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005). In principle, such low latitude can be accounted for by strong inclination shallowing in the sediment-derived Winter Coast and Zigan data.

Inclination shallowing is relatively common in fine-grained red sandstones and results in paleolatitudes that are systematically lower than in 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:

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

where I_0 = observed inclination, I_f = real field inclination, f = flattening factor where values <1 indicate the relative degree of flattening. I_0 may become close to zero for very small f values, i.e. after very strong shallowing, but it is physically impossible for the remanence vector to cross the horizontal plane and change sign (Fig. 10a).

The amount of flattening required to bring our Zigan results into agreement with those of Torsvik and Rehnström (2001) would require $f \sim 0.1$. Most inclination shallowing studies indicate f-values considerably higher (for example f = 0.6; Torsvik et al., 2012) and even experimental research indicates f-values in the range of 0.4–0.55 (Tauxe and Kent, 1984). Thus any explanation regarding inclination shallowing of the Zigan sediments requires values far exceeding anything observed in the laboratory.

Nevertheless, we made an attempt to address the magnitude of inclination shallowing in our results. We abstained from laboratory studies of magnetic anisotropy that are used for shallowing evaluation (Tan et al., 2003; Kodama, 2009) and instead analyzed the statistical properties of the observed data set in search of evidence for strong inclination shallowing. The first test is based on the fact that inclination shallowing gives rise to the far-sided effect for paleomagnetic poles if data from remote localities are compared. As noted above, the Zigan pole falls close to those published from the Winter Coast. In this case, the locality-to-pole great circles intersect at an acute angle making it difficult to reliably establish the far-sided effect (Fig. 9). Thus this test is inconclusive, and we can only state that the South Urals and Winter Coast data are to be either similarly shallowed, or not shallowed at all.

As noted above, any dataset that suffers from strong inclination shallowing will result in all unit inclinations to be of the same sign (for directions of one polarity, of course). In contrast, both signs should be present if the mean inclination is originally shallow, and some unit vectors fall beyond the equator simply because of natural scatter. In fact, the pattern may be somewhat smeared by experimental errors; if, as is usually the case, these errors are much less than the scatter created by natural sources, the difference between shallowed and originally shallow datasets will be clear. HTC unit vectors in the Zigan rocks form two nearly antipodal polarity groups, directions with similar declination and both positive and negative inclinations being present in each group (Fig. 5a). It becomes even clearer when all data are inverted to one polarity (Fig. 10b). When the data are transferred to the projection pole (Fig. 10c) it is clear that the entire distribution is nearly circular (Fisher, 1953), with elongation (E = 1.40) that is not statistically significant. Moreover, unit vectors with originally negative inclinations constitute a “lawful” part of the entire distribution and,

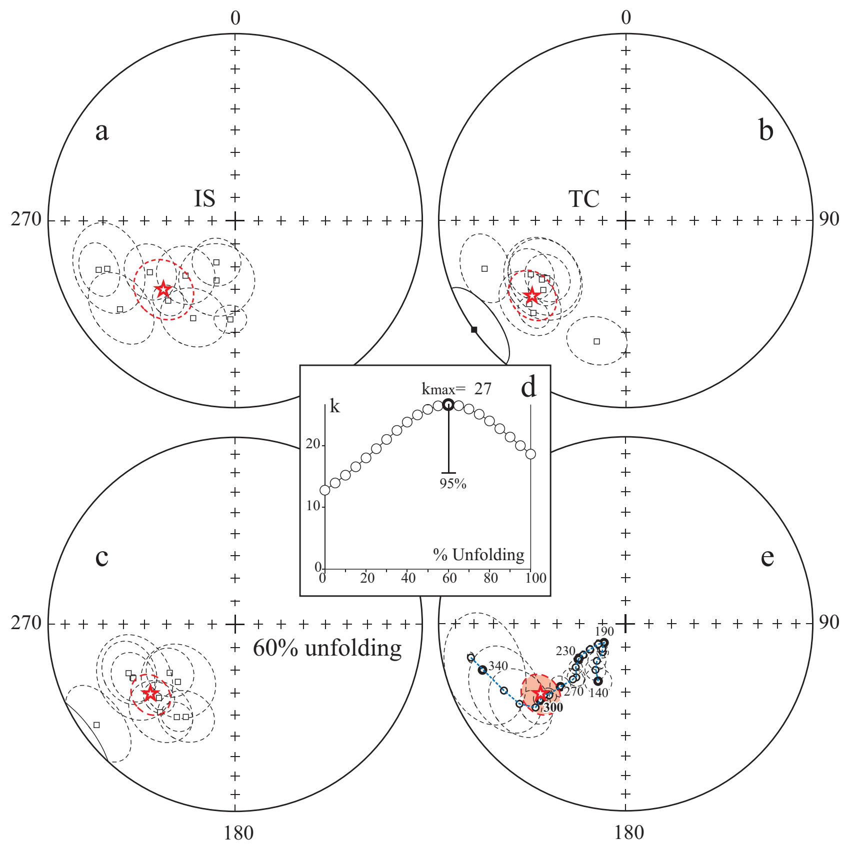

Fig. 8. (a–c) Directions of late Paleozoic overprint directions in situ (a), after tilt correction (b), and after 60% unfolding when the best grouping of site-mean directions is observed (c). Squares and thin lines are site mean directions with associated confidence circles; stars and thick lines are overall mean directions with associated confidence circles. (d) Plot of concentration parameter *k* versus degree of unfolding; maximum *k* value upon 60% unfolding is shown by thick symbol. (e) Stereoplot of reverse reference directions (circles connected with thick dotted blue line; thick for few selected points with presented ages) for 10 Ma intervals recalculated from 120 to 350 Ma segment of the APWP for Baltica (Torsvik and Cocks, 2005) to a point at 54° N, 57° E. Thin dashed lines are confidence circles for reference directions. Star and thick dashed line are same as in Fig. 8c. Other notation as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

clearly, are not streaked along the stereonet equator (thick solid line in Fig. 10c). Thus the second test unequivocally speaks against strong inclination shallowing.

Apart from reducing the mean inclination of a dataset, inclination shallowing distorts the original distribution of unit vectors by converting a circular distribution into a "banana" shaped distribution and increases the overall scatter (Fig. 10d; Bazhenov, 1981; Tauxe and Kent, 2004). As previously noted, an extremely strong inclination shallowing with $f \sim 0.1$ is required to bring our dataset ($I = 15°$) into agreement with those of Torsvik and Rehnström (2001). Simultaneously, a circular original distribution with mean inclination of about 70° would become more like a 'banana' with an elongation factor (E) of 8–10 (Fig. 10d). This effect is best visible if the "shallowed" distribution is transferred to the projection pole (Fig. 10e). The difference between a banana-type cloud expected for shallowed inclinations and the nearly circular distribution of our observed data is clear (Fig. 10c). Hence, it appears that no shallowing-related distortion is present in the Zigan HTC directions.

Two different tests indicate that no strong shallowing has affected the HTC in the Zigan rocks although we cannot rule out the presence of much weaker shallowing effect, of 5–15°. Even if present, however, this weaker effect does not change the main paleogeographic implication of the Zigan data that Baltica was at the low tropical latitudes in late Ediacaran time.

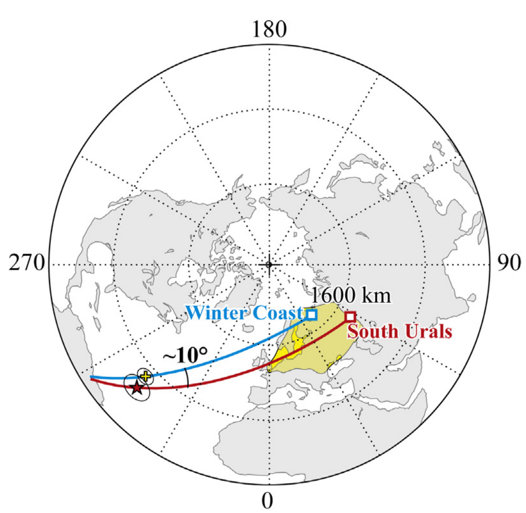

Fig. 9. Plot of the Zigan (star) and Winter Coast (cross) poles with associated confidence circles (thin lines) and locality-to-pole great circles (thick lines). Note that these great circles converge at an acute angle of ~10° and hence cannot be used for determination of the far-sided effect.

7. Paleogeographic implications

The Zigan pole, Z, shows an acceptable agreement with nearly coeval poles from the White Sea region, W (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005) and south Volynia, V (Elming et al., 2007). These Late Ediacaran poles for Baltica, ZWV poles, with the overall mean pole at Plat = 26.9° N, Plong = 299.2° E ($k = 35$, $A_{95} = 11.4°$, $N = 6$ poles), are different from the Phanerozoic APWP of Baltica (Fig. 6).

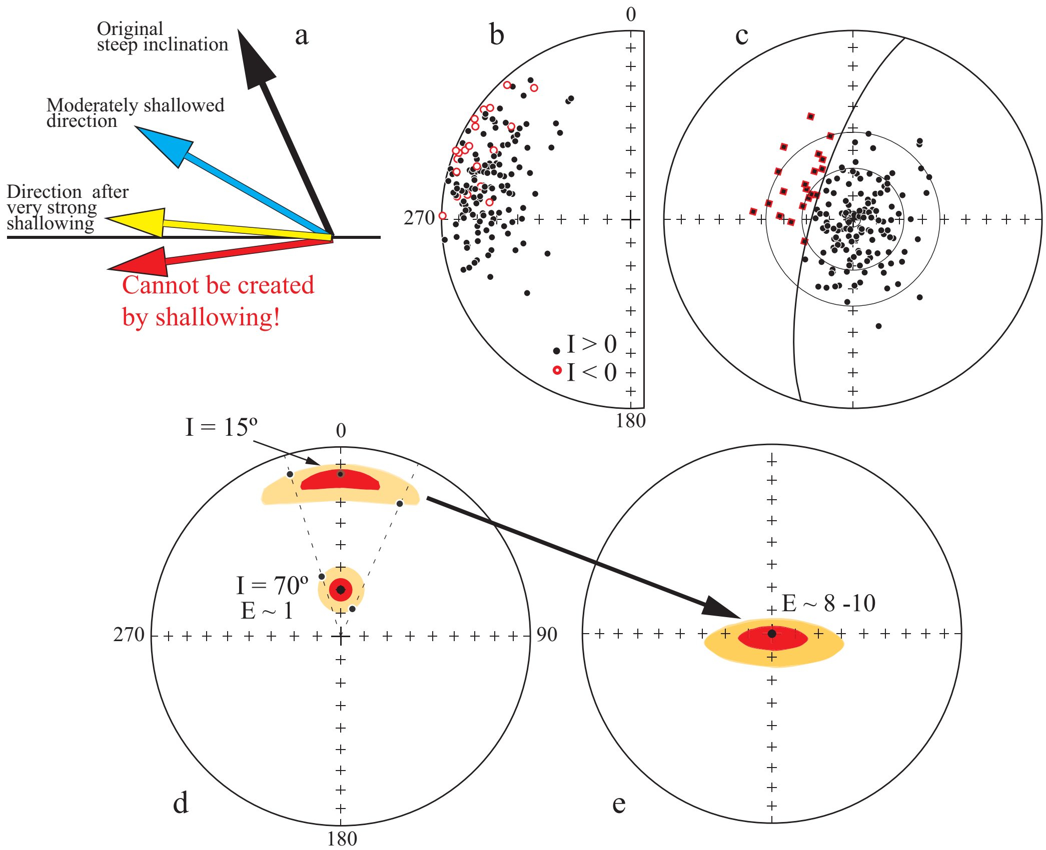

Fig. 10. (a) Cartoon showing that paleomagnetic inclination cannot change sign during inclination shallowing. (b) Stereoplot of unit HTC directions demonstrating that inclinations of both signs are present. (c) Same as (b) but centered on the stereonet pole. Directions with formerly negative inclination are shown as squares. Thick solid line is the trace of the stereonet equator in Fig. 10b. Thin circles are drawn to emphasize that unit vector distribution is nearly circular. (d) Cartoon illustrating how an original circular distribution with inclination $I = 70^\circ$ and elongation $E \sim 1$ is distorted by strong shallowing to a banana shaped one with inclination $I = 15^\circ$ and elongation $E \sim 8$–10. Differently colored parts are drawn to illustrate this distortion. Small black dots and connecting thin dashed lines denote the trajectories of two unit vectors. (e) Stereoplot of distorted distribution transferred to the pole of projection.

The very existence of the clear cluster of the low-latitude poles that are derived from remote parts of the craton is irrefutable, whereas the relatively large scatter of the ZWV poles may be connected with different factors, e.g. differences in rock ages or inclination shallowing in some results. The ZWV cluster places Baltica in the tropics near the end of Ediacaran time (Fig. 11).

Two polarities are clearly present in the Zigan data (Fig. 4), and the corresponding North poles must be in one of two positions

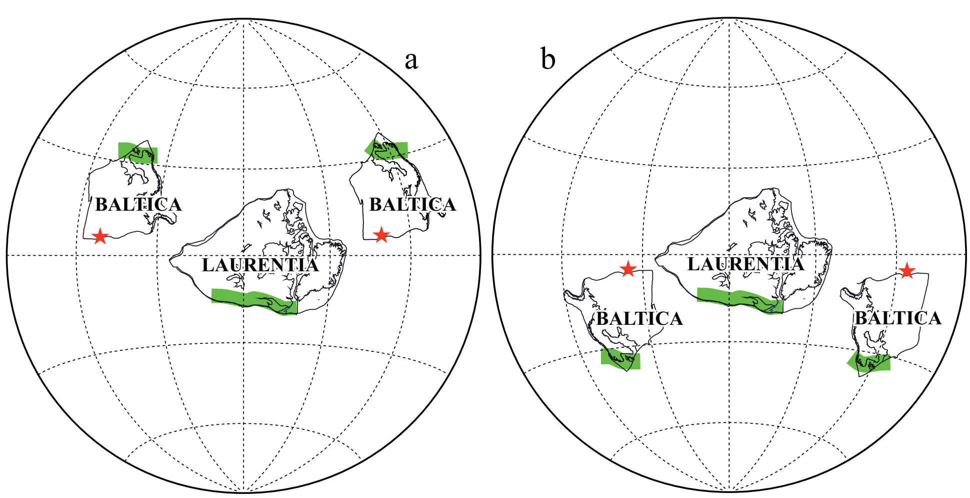

Fig. 11. Schematic reconstructions of Laurentia and Baltica. Laurentia is shown according to the 550 Ma North pole from the pole list in McCausland et al. (2007). Star denotes the South Urals. Green color denotes the margins of the late Neoproterozoic Iapetus Ocean. (A) Baltica is shown for the option that west-north-west directions ("PO1" pole) correspond to normal polarity. (B) Baltica is shown for the option that east-south-east directions ("PO2" pole) correspond to normal polarity. Note that longitudinal separation of Laurentia and Baltica is absolutely arbitrary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

"PO1" or "PO2"(Fig. 6a). Irrespective of the polarity choice, the Zigan pole and the mean Early Ordovician pole that is the oldest reliable pole on the Baltic APWP with known polarity are almost precisely 90° apart (Fig. 6a), thus making both polarity options equally plausible.

Two poles are tabulated for the very end of Ediacaran time them for Laurentia. The 550 ± 3 Ma Skinner Cove Formation result (McCausland and Hodych, 1998) is obtained at western Newfoundland, which is allocthonous upon Laurentia, but probably never was far away from the continent margin (Cawood et al., 2001; Hodych et al., 2004). This result, no matter how reliable it is, provides paleolatitudinal constraints only on the Laurentia paleoposition. Dual-polarity shallow directions are reported from the carbonate Johnnie Formation (Van Alstine and Gillett, 1979), but the age of the rocks is poorly constrained. Basing on the assumed age of the overlying rocks, Meert and Van der Voo (1994a,b) estimated the age of these carbonates as ca. 555 Ma. However, both poles suggest the low latitude paleoposition of Laurentia in the end of Ediacaran (McCausland et al., 2007).

By positioning Laurentia according to its 550 Ma north poles, there are two distinct relationships between the paleogeography of Baltica and Laurentia depending on the choice of north polarity in the ZVW poles (Fig. 11). Opening of the Iapetus Ocean between Baltica and Laurentia took place between 615 Ma and 550 Ma (Cawood et al., 2001; McCausland et al., 2007; Cocks and Torsvik, 2011). The late Ediacaran ZVW North Pole in its "PO1" option places Baltica in the northern hemisphere with its Iapetan margin facing north and separated by >5000 km from the other Laurentian Iapetan margin (Fig. 11a and b). Moreover, Baltica is in the wrong orientation with respect to its position during the closure of the Iapetus Ocean. If the "PO1" north polarity option is chosen, it would require Baltica to move southward by more than 5000 km and also rotate 180° between 550 Ma and the closure of Iapetus at ~425 Ma (Murphy et al., 2010). So, within the "PO1" north polarity option, if Baltica is placed to the east of Laurentia (Fig. 11a), its motions during the Iapetus existence are both fast and complicated, whereas placing Baltica west of Laurentia (Fig. 11b) leads to complicated kinematics and space problems with the future West Gondwana constituents, in particular, with Amazonia (e.g., Tohver et al., 2006; not shown).

The "PO2" north polarity option places Baltica in the southern tropics with its Uralian margin facing north. In terms of plate kinematics (both during opening and closure of Iapetus), the most logical longitudinal position for Baltica is east of Laurentia (Fig. 11c and d). This north polarity choice (and longitudinal placement) thus separates the two conjugate Iapetan margins by a "modest" ~1000 km and requires no gyrations for the later closure of Iapetus. Therefore, we corroborate the earlier conclusions of Popov et al. (2002, 2005) with a Late Ediacaran north pole for Baltica falling in the vicinity of present-day Australia and conclude that Baltica was east of Laurentia in tropical southern latitudes with the Uralian margin facing north in Late Ediacaran time (Fig. 11d).

It is only natural that the inferred paleogeography of Baltica (more generally, of any major tectonic unit) should be tested against data from other continental blocks. For instance, most end-Neoproterozoic global reconstructions (e.g., Cocks and Torsvik, 2011 and references therein) place Baltica at high southern latitudes at that time that is incompatible with our findings and hence requires revision. Detailed discussion of this swarm of interlaced problems, however, is outside the scope of this paper (see Meert, 2013).

The above interpretation and discussion are entirely based on the assumption that "low-latitude" Late Ediacaran ZWV poles are correct indicators of the paleolatitude. As there are the "other" poles from Baltica that indicate a high-latitude position for the craton and are of similar Late Ediacaran ages as the ZWV data, with the exception of the E pole (Figs. 1b and 5b; Table 1), their origin and significance merit a brief discussion. First of all, we would like to stress that no quick jumps of field directions were found either among the Zigan datasets or the Winter Coast. As noted by Popov et al. (2002), the Early Cambrian Tornetrask pole (Torsvik and Rehnström, 2001) falls amidst the early Mesozoic data for Baltica. The same is true for the pole for the so-called Alno steep component (Meert et al., 2007). The similarity of the Fen data and late Paleozoic pole for Baltica is also well known (Meert et al., 1998; Meert, 2013). Finally, the apparently reliable 616 Ma Egersund pole (Walderhaug et al., 2007) is suspiciously close to the Early Ordovician segment of the Baltic APWP. Hence, all these data may be connected with several remagnetization events that vary in space and time, and two Ediacaran poles only, the Alno shallow component and North Volynia pole, remain unaccounted-for (Fig. 5b). Of these two, the pole VN from North Volynia that is based on the studies of two lava units and presumably two tuff units and has large error limit A95 of ~28° (Elming et al., 2007). Finally, note that the scattered Alno dataset was divided into a more compact "steep" and diffuse "shallow" components (Meert et al., 2007), and the arbitrariness of this procedure as well as possible fictitiousness of the latter remanence was stressed by Meert et al. (2007).

Hence, the Baltic paleomagnetic data reveal no solid ground for the conceptions of high-latitude Baltica in the Late Ediacaran, superfast motions of the cratons (McCausland et al., 2007) or complex field geometry (Abrajevitch and Van der Voo, 2010; Meert, 2013). In sum, both orientation and the position of Baltica in low southern latitudes by the end of the Ediacaran appear to be firmly established. The future studies must both construct a reliable connection between the Late Ediacaran and Early Ordovician poles for this craton, on one hand, and extend the paleomagnetic record to older times, on the other.

8. Conclusions

We carried out geochronological and paleomagnetic studies of terrigenous rocks of the Zigan Fm. (the youngest member of the Asha Series) from the westernmost tectonic units of the Ural fold belt located at deformed eastern margin of Baltica along with Paleozoic rocks from the same region. Depending upon regional correlation of the Asha Series members, U-Pb age of of 547.6 ± 3.8 Ma on magmatic zircons from an ash bed within these clastics either corresponds to the depositional age of the Zigan Fm., or the age of this formation is confined to the 550–542 Ma interval. With the aid of stepwise thermal demagnetization, a dual polarity high-temperature remanence was successfully isolated from red beds of the Zigan Fm. This remanence resides in hematite and is likely primary as indicated by the presence of a positive reversal test and regional consistency test. Several lines of evidence imply that this remanence was not affected by strong inclination shallowing and therefore, the observed inclination of ca. 15° can be taken as the correct indication of the eastern margin of Baltica by the end of the Ediacaran. Geological data indicate that the study area was a part of the Baltic craton at least since the early Neoproterozoic, while paleomagnetic results on Paleozoic rocks from the westernmost zones of the Ural fold belt reveal not local and regional rotation with respect to Baltica. We think that new data resolve the existing controversies on possible position of this continent in the global paleogeography at the Precambrian–Cambrian transition.

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