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Ages of detrital zircons (U/Pb, LA-ICP-MS) from the Latest Neoproterozoic–Middle Cambrian(?) Asha Group and Early Devonian Takaty Formation, the Southwestern Urals: A test of an Australia-Baltica connection within Rodinia

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ABSTRACT

A study of U-Pb ages on detrital zircons derived from sedimentary sequences in the western flank of Urals (para-autochthonous or autochthonous with Baltica) was undertaken in order to ascertain/test source models and paleogeography of the region in the Neoproterozoic. Samples were collected from the Ediacaran-Cambrian(?) age Asha Group (Basu and Kukkarauk Formations) and the Early Devonian-aged Takaty Formation.

Ages of detrital zircons within the Basu Formation fall within the interval 2900–700 Ma; from the Kukkarauk Formation from 3200 to 620 Ma. Ages of detrital zircons from the Devonian age Takaty Formation are confined to the Paleoproterozoic and Archean (3050–1850 Ma). Potential source regions for the Asha Group detrital zircons include the Eastern European platform, Amazonia and West Africa based on 'archetypal' Rodinia reconstructions and Late Neoproterozoic paleogeographic models. An alternate proposal places Australia adjacent to Arctic/Uralian margin of Baltica (so-called Australia upside-down concept).

A comparison between detrital zircon populations from the Asha Series and East European Platform source regions demonstrate an unusual dichotomy in that distal sources appear to contribute more zircon than near source regions. This dichotomy is examined and we note that Australia contains source regions of the proper age range to match the Uralian signal and therefore, the placement of Australia against the Arctic/Uralian margin of Baltica is compatible with the detrital zircon record. We also note that an Ediacaran position of Baltica against Australia presents a paleogeographic conundrum and therefore if the Australia upside-down concept is reasonable, the breakup between Australia and Baltica must have occurred prior to the Ediacaran and most likely in the 700–750 Ma interval.

Although sedimentary strata of the southwestern form a continuous section, the spectrum of detrital zircon ages within the Asha Group and Takaty Formation indicates major changes in basinal source and structure. The basin was most likely an intracontinental) basin during the Tonian/Cryogenian interval and perhaps into the Ediacaran. Later, during accumulation of Takaty Fm. (Early Devonian), the basin formed along a passive margin with input from the western side of the East European Platform.

1. Introduction

The eastern boundary of East European Platform (EEP) is the present-day N-S trending Ural Mountains (the Urals; Fig. 1). The Uralide Orogen is a part of the Paleozoic fold-thrust belt formed during the final stages of northern Pangea assembly. During this orogenic cycle, the Uralian Ocean closed between Baltica-Laurentia and Siberia-Kazakhstania along the Uralian suture (or Main Uralian Fault; Hamilton, 1970; Zonenshain et al., 1990; Sengör et al., 1993; Puchkov, 2000, 2002, 2009, 2010; Kuznetsov et al., 2010a; Görz and Hielscher, 2010).

The Uralian orogeny exposed Late Cambrian to Late Paleozoic rocks that collectively form the Uralides. In contrast, older rock complexes in, and west of, the Urals are collectively named the Pre-Uralides-Timanides. The Pre-Uralides-Timanides are separated from the Uralides either by stratigraphic differences or structural boundaries. The subdivision between the two was initially made by Kheraskov (1948).

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Along strike, the Urals is subdivided into the *Eastern-Uralian* and *Western-Uralian* (∼western slope of the Urals) megazones. The *Main Uralian Fault* separates the two regions. The eastern Uralides are mostly covered by younger sediments, but are generally thought to be allochthonous with respect to the Uralian edge of the Baltica-Laurussia. The Western-Uralian megazone contains both the Uralides and the Pre-Uralides-Timanides.

Many geological aspects of the Uralides (e.g., relations of individual sequences of different scale, their biostratigraphic and isotopic-geochronological characteristics) are presently well understood and led to a reasonably coherent geodynamic history of the Uralide Orogeny (see the most recent review-articles Brown et al., 2006; Fershtater et al., 2007, 2010; Puchkov, 2002, 2009, 2010; Ryazantsev et al., 2008, 2012). Even so, many key questions regarding the Pre-Uralian history (recorded and partially preserved in Pre-Uralides–Timanides complexes) remain to be answered or are still debated. Among the debated topics are the duration of the Uralian Ocean and existence of a Paleo-Uralian ocean that closed prior to the opening/closing of the Uralian Ocean. Some researchers argue that Uralian Ocean opened in the Ordovician (Ivanov et al., 1986; Puchkov, 2002, 2010; and others), whereas others believe there was a "Pre-Uralian" ocean that opened in the Late Precambrian (Samygin and Leites, 1986; Samygin and Ruzhentsev, 2003; Samygin and Kheraskova, 2005; Kuznetsov, 2009). The late Precambrian to Cambrian sedimentary basins now occupying the western Uralian megazone may hold key clues that can help trace the pre-Ordovician history of the Uralian margin.

Our examination of the early evolution of the Uralian margin is inextricably tied to the tectonic history of the EEP and its relationship to the assembly and dispersal of the Columbia (Rogers and

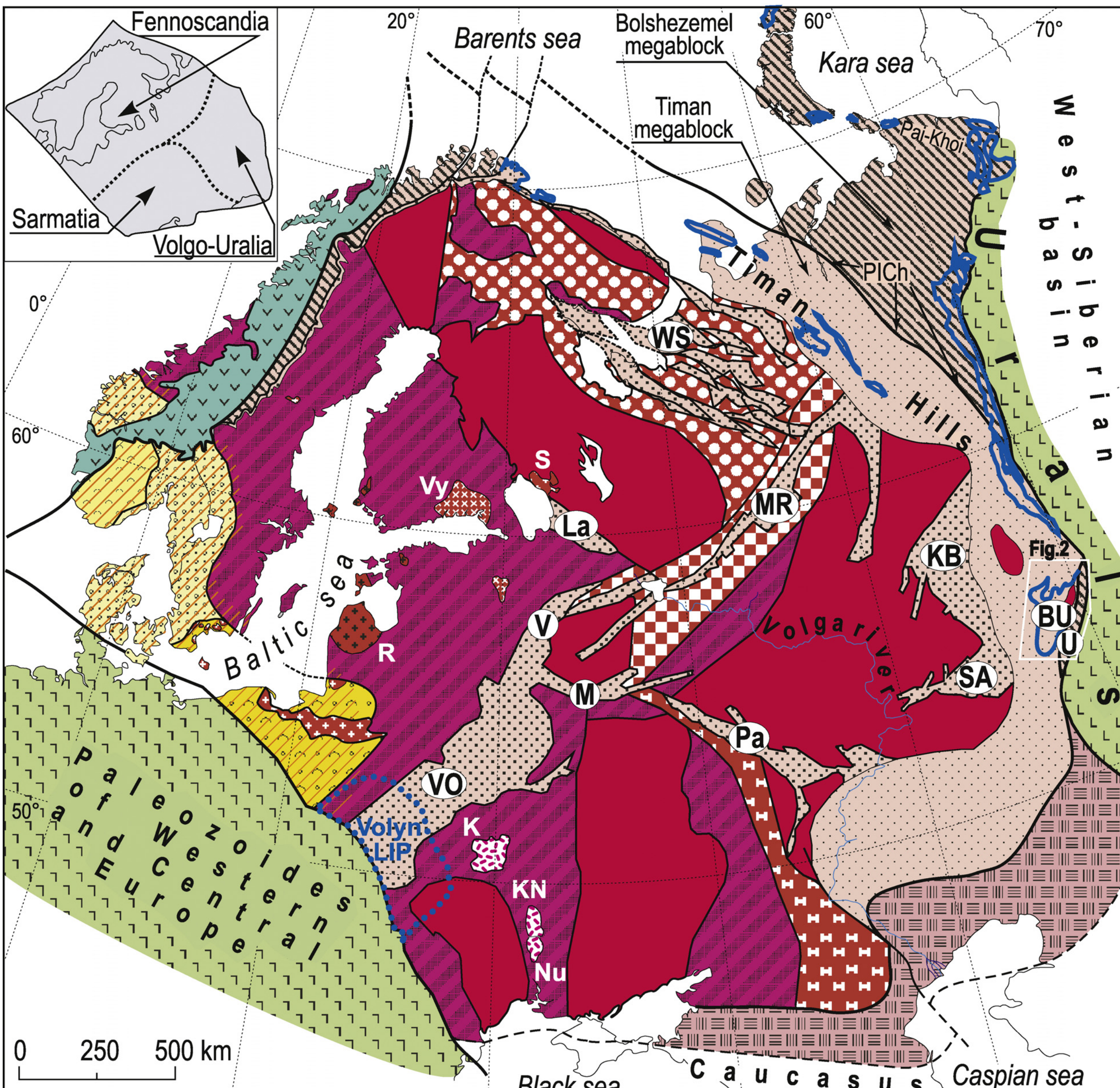

Fig. 1. Map of the main basement complexes and structures of the East European Platform (EEP) and its periphery, including blocks of consolidated basement, rift structures, and Neoproterozoic and Paleozoic fold-thrust belts (modified from Kuznetsov et al., 2010a). Late Paleoproterozoic–early Neoproterozoic complexes of the EEP from Bogdanova et al. (2008). Neoproterozoic–Middle Cambrian complexes at the eastern and northeastern periphery of the EEP after Kuznetsov et al. (2007) and Kuznetsov (2009). Configuration of the White Sea Rift System after Baluev (2006). Insert: Contours of EEP proto-cratons Fennoscandia, Sarmatia and Volga-Uralia simplified from Bogdanova et al. (2008). Plutons: K, Korosten; KN, Korsun'-Novomyrgorod; Nu, Novoukrainskiy; Vy, Vyborg; R, Riga; S, Salmi; B, Bornholm.

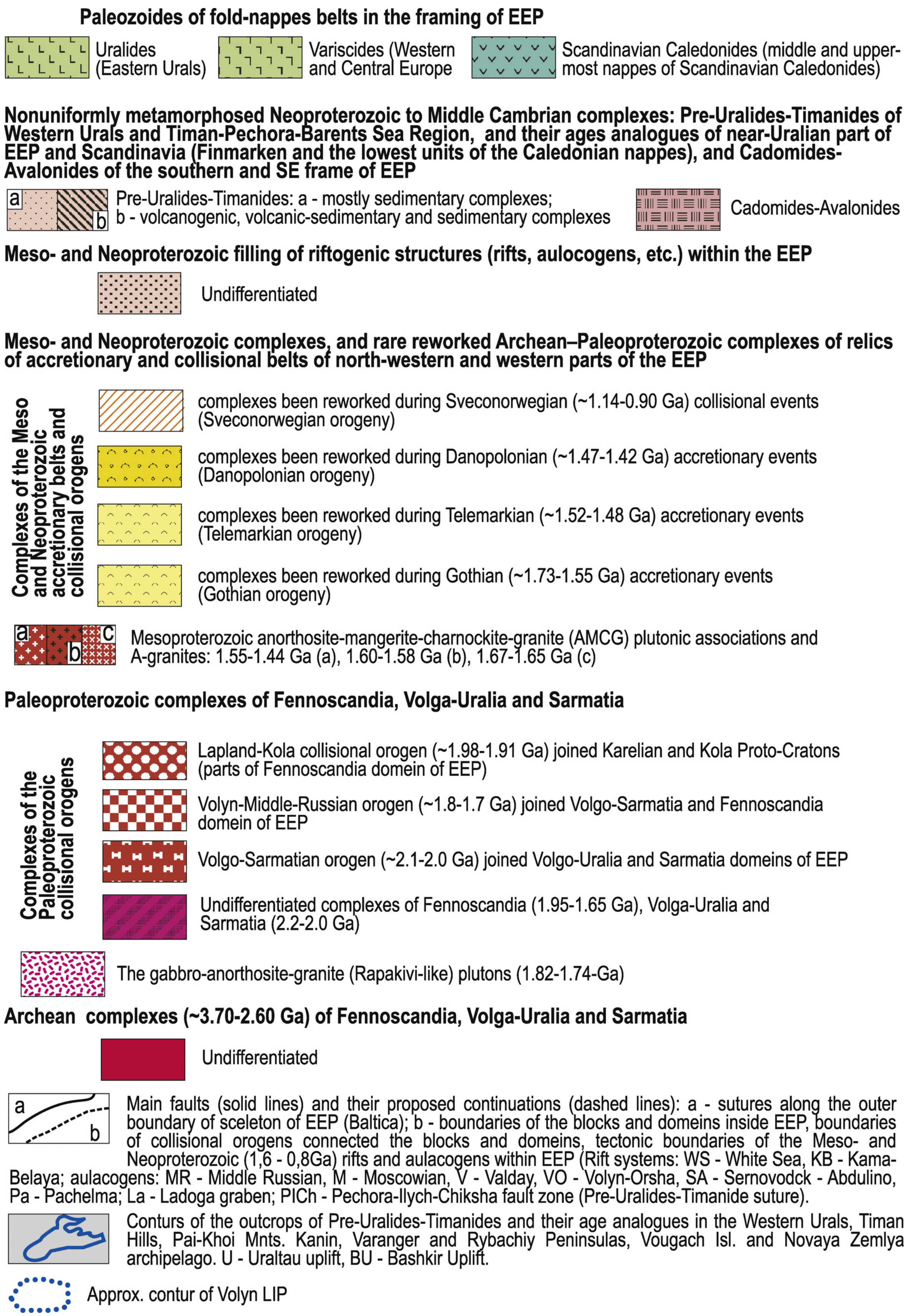

Fig. 1. (*Continued*).

Santosh, 2002; Meert, 2002, 2012) and Rodinia (Li et al., 2008) supercontinents. It was recently proposed that the Paleoproterozoic basement of the EEP was formed between ca. 2.1 and 1.8 Ga as a part of Paleoproterozoic supercontinent Columbia (Rogers and Santosh, 2002; Zhao et al., 2004). As Columbia broke apart, Proto-Baltica became isolated and later incorporated into the Rodinia supercontinent. Alternatively, it is possible that Proto-Baltica remained attached to Laurentia throughout the Columbia-Rodinia supercontinents and only became a separate block (Baltica) during the opening of the Ediacaran Iapetus Ocean (Meert and Powell, 2001; Hartz and Torsvik, 2002; Bogdanova et al., 2008; Li et al., 2008; Evans, 2009; Piper, 2000, 2007; Swanson-Hysell et al., 2012). Although there is a general consensus that Proterozoic supercontinents assembled and dispersed, the exact configuration of those supercontinents is strongly debated (Swanson-Hysell et al., 2012; Meert, 2012; Meert and Torsvik, 2003; Evans, 2009; Piper, 2007). The existence or absence of a Late Neoproterozoic–Cambrian Paleo-Uralian ocean is a strong constraint for positioning Proto-Baltica within Rodinia. Was the Uralian edge of Proto-Baltica a passive margin or it was proximal to another landmass?

In this paper we examine the stratigraphy and detrital zircon record of a sequence of thick and expansive clastic sedimentary sequence in the southern part of the Western Urals. These sediments accumulated during the Neoproterozoic-Paleozoic and were formed during the initial opening of the Uralian Ocean in the early Paleozoic (Ivanov et al., 1986).

2. Pre-Uralides–Timanides of the Bashkir Uplift (southern part of the Western Urals)

The Central Uralian uplift is composed of a range of submeridional rises extending along the length of the Urals. Structurally, it is made up of large uplifts and anticlinoriums of Pre-Uralides–Timanides complexes lying among the Uralian and Neo-Uralian complexes of the West Uralian megazone (Kuznetsov et al., 2006, 2007, 2010a; Kuznetsov, 2009; Puchkov, 2000, 2003, 2010). The Bashkirian uplift (BU) is the largest structural element of the southern part of the Central Uralian uplift. In the north, west, and south, the BU borders structures composed of Paleozoic deposits of the Western-Uralian megazone. In the east, the BU borders the non-uniformly deformed and metamorphosed Paleozoic and Precambrian complexes of the Uraltau uplift (Fig. 2).

The lower horizons in the BU are represented by an Archean and Paleoproterozoic gneiss-amphibolite complex with granulitic relics known as the Taratash metamorphic complex (TMC). The TMC is exposed in the northern part of the BU in the core of Taratash anticline (Lennykh et al., 1978; Sindern et al., 2005; Puchkov, 2010 and references therein). The upper structural element of Pre-Uralides–Timanides in the BU is represented by a sequence composed of terrigenous, terrigenous-carbonate, carbonate and rare volcanogenic and volcanogenic-sedimentary rocks up to 10–12 km in thickness (Puchkov, 2010; Maslov, 2004). The upper sequence lies stratigraphically over the TMC, with structural unconformity. The sedimentary section is divided into two parts. The lower (and thicker) part of the sequence is the Riphean Supergroup (Stratotype. . ., 1983; Kozlov, 1982; Kozlov et al., 1989; Maslov, 2004). The upper part of the sedimentary sequence is up to 1500 m thick and is composed of interlayered siltstones, sandstones, and conglomerates of arkosic and polymictic composition known as the Asha Group. The age of the Asha Group is debated and estimates range from Upper Neoproterozoic to Middle Cambrian (Kozlov, 1982; Bekker, 1968, 1992, 1996; Kuznetsov and Shazillo, 2011).

Based on the lithological characteristics of different parts of the sequence, the Asha Group is subdivided into several lithostratigraphic units (Formations) known as (from oldest to youngest) the Bakeevo, Uryuk, Basu, Kukkarauk, and Zigan Formations (Fig. 2; Stratotype. . ., 1983; Kozlov, 1982; Bekker, 1996; Puchkov, 2010; Maslov, 2004). Age constraints for the Asha Group are based on a combination of recent geochronological work, paleontological evidence and correlation with other units in the northern and central Urals (Grazhdankin et al., 2011). Ediacaran biota are reported from multiple units within the Asha Group (Bekker, 1968, 1992, 1996), the age of these deposits was therefore assumed to be Ediacaran (Puchkov, 2010; Maslov, 2004). Recent U-Pb geochronological data from interbedded tuffs support this contention (Grazhdankin et al., 2011) along with additional fossil discoveries (Kolesnikov et al., 2012). Recently, Kuznetsov and Shazillo (2011) report the discovery of numerous fine fragments of inarticulate brachiopods within the Kukkarauk Fm. These fragments are very small (ranging from 1 mm to several hundred μm) thought to belong to the Obolidae Family. The first appearance datum (FAD) for the Obilidae takes place in the Botomian (~515 Ma). There is some disagreement about the significance of these 'fossils' as well as their identification. For example, Puchkov (2012) has argued that the fossils are more diagnostic of Nemakit-Daldyn biota (~542–525 Ma). Additional support for a Cambrian-age of the Kukkarauk Formation comes from early detrital zircon (and Ar-Ar) work reported by Willner et al. (2003) and Glasmacher et al. (1999) where ages ~515 Ma appear in the detrital record. In contrast, Levashova et al. (2013) report a U-Pb age on zircon from a tuff within the Zigan Formation of 548 ± 3 Ma that would relegate the bulk of the Asha Group to the Ediacaran. Several very thin tuff layers were found in the Chernykamen Formation of the Sylva Group. Magmatic zircons from these tuff layers were dated (U-Pb, SHRIMP) as 557 ± 13 Ma (Maslov et al., 2006). While the significance of the paleontological finds must await further verification, it seems clear that the age of the Kukkarauk and Zigan Formations should be placed near the Ediacaran-Cambrian boundary (see also Grazhdankin et al., 2011).

The Asha Group rests unconformably above the Riphean Supergroup and is unconformably overlain by Paleozoic deposits. The oldest sedimentary units overlying the Asha Group are thought to be Lower Devonian in age (Takaty Formation) in the western part of the BU and of Middle Ordovician age in the south (Puchkov, 2000, 2009, 2010). The Takaty Formation can be found along the western slope of the Southern, Middle and Northern Urals. Its stratotype locality is found along the Takaty River (South Urals) where the Late Emsian (~400 Ma) age is paleontologically constrained (Ivanushkin et al., 2009). The Takaty Formation is underlain by an erosional unconformity on older strata and is conformably overlain by carbonate units that are nearly continuous from the Middle Devonian to Lower Permian. The Takaty Formation is dominated by monomictic or oligomictic quartz sandstones that show very little (if any) regional differences in lithology suggesting that source material for sandstones was the same along the western slope of the Southern, Middle and Northern Urals.

3. Sampling and dating of the detrital zircons

3.1. Sampling of the rocks

Samples 09-027 and 09-041 for detrital zircons were taken along the stratotype section of the Asha Group, from Kukkarauk Creek. Sample 09-027 (Basu Formation) was taken (53°35′50.3″N; 56°46′25.0″E) on the eastern side of a small roadside open pit located 50 m south of Sterlitamak–Makarovo–Kulgunino highway. The Basu Formation here is composed of dirty green, fine- and mid-grained polymictic sandstones with a significant admixture of white mica flakes on bedding surfaces. Slumps (gravity slide

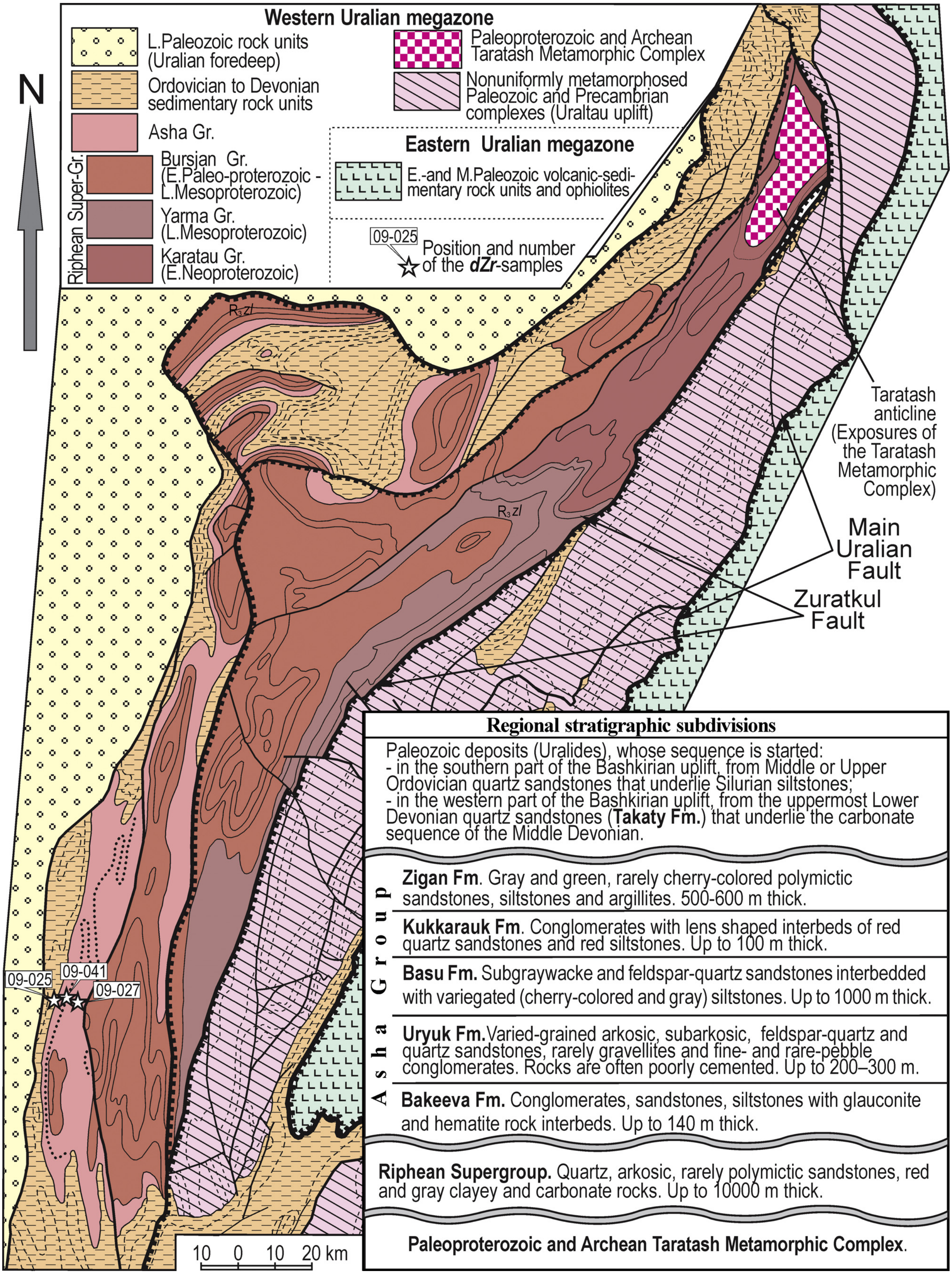

Fig. 2. Map of the geological structural setting and stratigraphic subdivisions within the region of the Bashkirian Uplift.

Fig. 3. Photo of sandstones of Basu Fm. A slump among subgraywacke sandstones.

Fig. 4. Photo of conglomerates of Kukkarauk Formation with lenses and thin layers of red sandstones.

folds) are sometimes observed in the outcrop (Fig. 3). Sample 09-041 (Kukkarauk Fm.) was taken (53°36′04.6″N; 56°41′06.2″E) from a coarse-grained red sandstone found as a lens within conglomerates of the Kukkarauk Formation along the bank of Kukkarauk Creek (Fig. 4). Sample (09-025) was taken from a quartz sandstone of the Takaty Formation near the confluence of the Sikaza River and Kukkarauk Creek (53°36′41″N, 56°39′28″E).

Each sampled weighed approximately 1 kg. Care was taken to prevent contamination (or cross-contamination) during manual disintegration in a cast iron mortar. Samples were pulverized to a size less than 0.16 mm and then density filtered on a water table. Heavier fractions were further isolated using variable density liquids. Individual zircon grains were then hand-picked and mounted in epoxy for analysis.

Gross morphologies of the zircons from sample 09-027 included rounded to subrounded bi-pyramidal crystals. The typical crystals are yellowish pink, light pink or pink in color, transparent, to semi-transparent (a few more opaque grains were also present) and about 100 μm or less in size.

Zircons from sample 09-041 are represented by semi-rounded and occasional well to very well rounded pink grains ranging in size from 50 to 100 μm. An intense luster and more rarely grains with dull surfaces characterize many grains.

Fragments of rounded crystals dominate zircons from sample 09-025. There are small yellowish to transparent grains that commonly preserve a crystalline form (weakly rounded) and larger colorless to light pink transparent grains.

Zircon U–Pb analyses were carried out at the Department of Geological Sciences, University of Florida, using the "Nu-Plasma" (Nu Instruments, UK) multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICP-MS). The mounted zircon grains were ablated using an attached New Wave 213 nm ultraviolet laser, using a laser spot size of 30 μm for U–Pb analyses (Turner et al., 2013; Malone et al., 2008). Ar and He carrier gas was used for sample transport into the mass spectrometer. Before each ablation, a "zero" measurement was taken for 20 s in order to make on-line corrections for isobaric interferences, especially from ^{204}Hg, a common component of argon gas. Following this "zero" period, laser ablation commenced for 30 s, keeping a constant ablation pit depth, therefore reducing elemental fractionation. Ablations occurred in intervals of 10 zircons, directly preceded and followed by ablation of 2 FC-1 standard zircons. The raw isotopic data garnered from the LA-MC-ICP-MS were imported into a Microsoft Excel® spreadsheet (Calamari) where corrections for instrumental drift and mass bias were undertaken by normalization to standard zircon FC-1 from the Duluth Gabbro, dated at 1099.0 ± 0.7 Ma and 1099.1 ± 0.5 Ma by Mattinson (2010). Figures were generated and errors calculated using Isoplot/Ex plotting software Version 4.11 by Ludwig (2008). Common lead corrections were not applied to the data; however, ^{204}Pb counts are monitored in each sample and the standards. Any zircon with a ^{204}Pb count exceeding one standard deviation above the FC-1 mean was rejected from the collection as well as any zircon that yielded ^{206}Pb/^{238}U ages that were more than 10% discordant from their ^{207}Pb/^{206}Pb ages. For grains older than 1000 Ma, ^{207}Pb/^{206}Pb ages were used and for grains <1000 Ma, ^{206}Pb/^{238}U ages are used.

3.2. Dating of detrital zircons

The Basu Formation (sample 09-027) yielded a total of 78 analyses with ages ranging from 2589 to 755 (Fig. 5). Three rather distinct populations are observed in the Meso to Paleoproterozoic time spans from 1338 to 1105 Ma (23 grains); 1593 to 1454 Ma (23 grains) and 2095 to 1652 Ma (24 grains). Both Mesoproterozoic populations are unimodal with clear age peaks (maximum density probability – ***MDP***) at 1501 Ma and 1213 Ma. The Paleoproterozoic population has two ***MDP*** at 2000 and 1907 Ma. Less dominant populations (4 zircons or 5% and 3 zircons or 4%) had ages that fell within the 1060–959 Ma and 2869–2704 Ma intervals.

For Kukkarauk Formation (sample 09-041) 57 analyses yielded concordant ages that range from 3188 to 617 Ma (Fig. 5). The dominant population (20 zircons) range in age from 1700 Ma to ~1300 Ma with an ***MDP*** of 1465 Ma. A somewhat smaller Late Mesoproterozoic population (11 grains) ranges between 1231 and 1099 Ma with an ***MDP*** of 1195 Ma. The remaining zircons (15 grains) are of Paleoproterozoic to Neoarchean age ranging from 2097 to 1923 Ma (***MDP*** at 1987 Ma) and from 2850 to 2644 Ma with no well-defined ***MDP***.

The sample from the Takaty Formation yielded 44 concordant ages that fall between 3050 and 1860 Ma (Fig. 5). Within this range, it is possible to discern at least 3 distinct populations. The youngest (Paleoproterozoic) population is represented by 19 grains with an ***MDP*** of 1920 and a rather narrow age span of 2150–1860 Ma. The remaining two zircon populations are mostly Archean in age with an older grouping at 3042 Ma (***MDP*** 8 grains) and a younger grouping with two ***MDP*** peaks at 2640 Ma and 2424 Ma (early Paleoproterozoic). We note a very large (nearly 1.5 Ga!) "gap" between the sedimentary age of sandstones from Takaty Formation (~400 Ma) and the age of the youngest of dated zircon (~1.86 Ga).

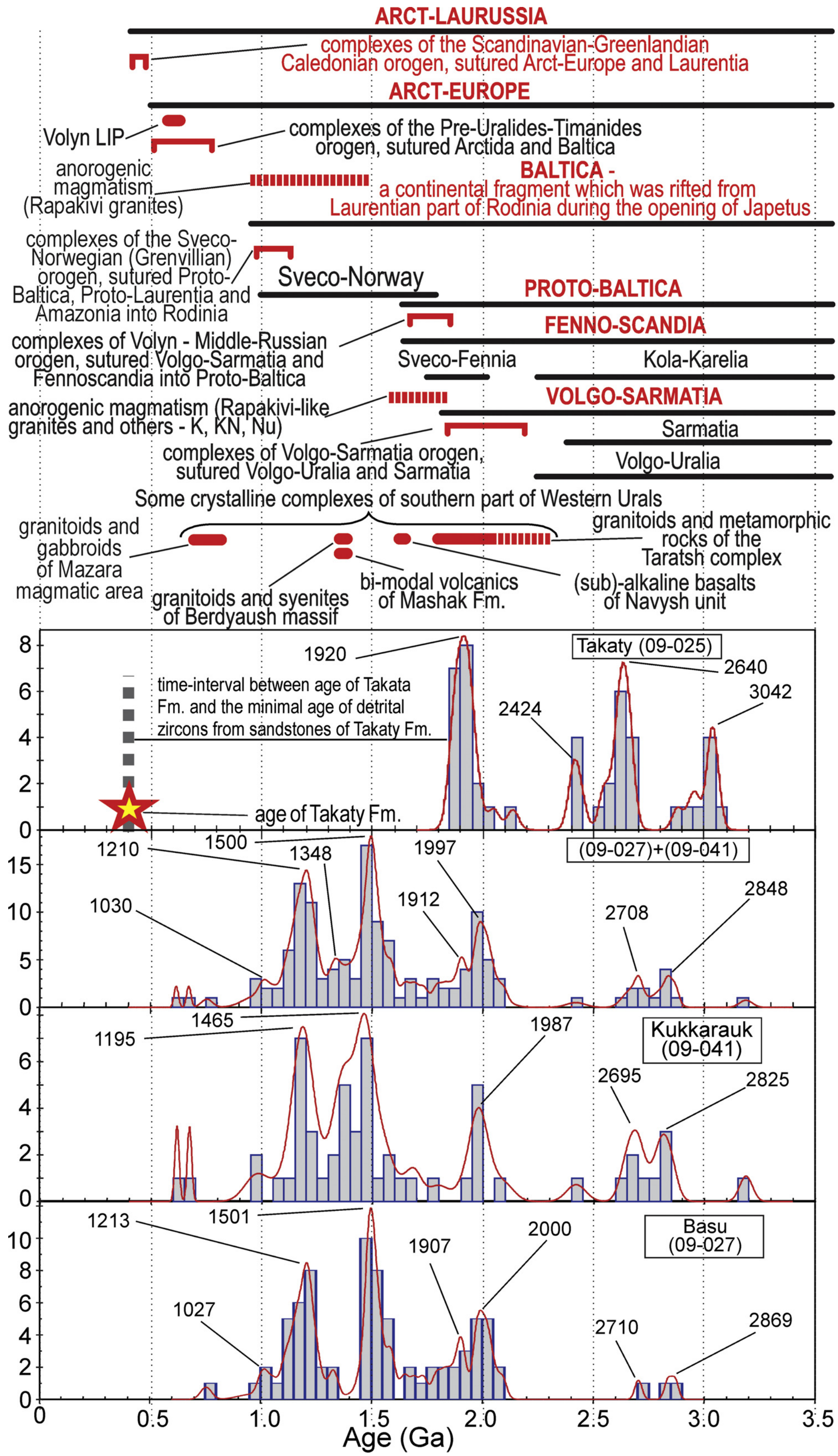

Fig. 5. Histograms and density probability plots for detrital zircon ages obtained from the Basu (09-027) Formation and the Kukkarauk Formation (09-041) of the Asha Group along with results from the Devonian-aged Takaty Formation (09-025). The upper section of the figure shows the major time intervals bracketing the main tectonic events within the EEP and surrounding regions.

Table 1
p value results from the Kolmogorov–Smirnov statistical test (using error in the CDF) for all samples discussed. White, *p* values less than 0.05; yellow, *p* values greater than 0.05. For discussion, see text. (For interpretation of the references to color in the table, the reader is referred to the web version of this article.).

	Basu (09-027)	Kukkarauk (09-041)	(09-027) + (09-041)	Cape River Quartzite (CR190)	Marino Arkose (AFB123136)	Bonney Sandstone (AFB123140)	Takaty (09-025)
Basu (09_027)		**0.529**	**0.999**	**0.654**	**0.663**	**0.212**	0.000
Kukkarauk (09-041)	**0.529**		**0.909**	**0.567**	**0.387**	**0.217**	0.000
(09-027) + (09-041)	**0.999**	**0.909**		**0.573**	**0.474**	**0.142**	0.000
Cape River Quartzite (CR190)	**0.654**	**0.567**	**0.573**		**0.363**	**0.884**	0.000
Marino Arkose (AFB123136)	**0.663**	**0.387**	**0.474**	**0.363**		**0.106**	0.000
Bonney Sandstone (AFB123140)	**0.212**	**0.217**	**0.142**	**0.884**	**0.106**		0.000
Takaty (09-025)	0.000	0.000	0.000	0.000	0.000	0.000	

Note: Plotting of the graphs (Fig. 6) and KS-test implementation were made in the MS Excel program using the macros developed by G. Gehrels and J. Guynn (Department of Geosciences, University of Arizona, Tucson, United States), https://sites.google.com/a/laserchron.org/laserchron/home/.

4. Source comparison analyses

To compare the obtained dates for detrital zircons from samples 09-027 (Basu Formation) and 09-041 (Kukkarauk Formation), we applied the Kolmogorov–Smirnov test (KS-test) to their cumulative age distributions. The comparison of the derived set of ages (Table 1, Fig. 6) has shown a high degree of similarity between the samples ($p = 0.529$). In spite of the different lithologies sampled (i.e. polymict sandstones versus arkosic sandstones), there are no substantial differences in the age distributions of the detrital zircons. Given that both sequences appear to have sourced similar regions, we combine both data sets as an integrated database for the Asha Group and conclude that both received input from the same source regions.

We then take the combined "Asha Group" detrital zircon profile and compare the results to those obtained from the Devonian-aged Takaty Formation. In general, the EEP is considered to be the most likely source (western-derived in present-day coordinates) for clastic material in both the Takaty Formation and the Asha Group. A second possibility is that these sediments entered the basins from nearby local sources or from hypothetical 'eastern' sources that are not part of the EEP (i.e. reworked detrital zircons).

Potential source regions in the immediate vicinity of the basinal sediments include Precambrian basement complexes (both igneous and metamorphic) including the following units:

(1) Taratash metamorphic complex: The Taratash includes granulites and amphibolites. The oldest known material in the Taratash is derived from relic zircons dated to between 3.5 and 2.6 Ga (Krasnobayev, 1986; Sindern et al., 2005; Ronkin et al. (2007a,b). Metamorphic ages within the Taratash range from 2.1 to 1.8 Ga.
(2) Ai Formation: This formation includes subalkaline basalts (~1.64 Ga) of the Navysh volcanic unit at the base of the Riphean Supergroup (Stratotype, 1983; Kozlov et al., 1989).
(3) Mashak Suite: This unit is composed of bimodal volcanic rocks dated to 1.38 Ga (Ernst et al., 2006; Puchkov et al., 2009; Puchkov, 2010; Ronkin et al., 2005a).
(4) Berdyaush Massif: Includes granitoids, syenites and nepheline syenites (~1.38 Ga; Krasnobaev et al., 1984; Ronkin et al., 2005b).
(5) Kusa-Kopan, Akhmerovo and Gubensky Complexes: Composed of gabbro-norites, granitic gneisses, granitoids and granites ranging in age from 1.39 to 1.33 Ga (Krasnobaev et al., 2006, 2008; Kholodnov et al., 2006; Puchkov, 2010).
(6) Mazara Massif: Includes granitoids and gabbros with ages of 680–665 Ma and 710–705 Ma (Kuznetsov, 2009).

Potential source regions from within the EEP are located in four large crustal blocks in Karelia, Kola (Baltic/Fennoscandian shield), Sarmatia (Ukrainian Shield) and Volga-Uralia. These four regions all contain significant tracts of Archean-age crust (Mints et al., 2010). Within the Baltic/Fennoscandian shield, the main events associated with the assembly of the platform occurred between 2.1 and 2.6 Ga (Bayanova, 2004; Bibikova et al., 2005; Glebovitskii, 2005; Hölttä et al., 2008; Chashchin et al., 2008; Slabunov et al., 2006; Slabunov, 2008).

Vast exposures of the Sarmatia crustal province outcrop on the Ukrainian shield and are found in the Voronezh basement uplift that is covered by very thin (10–100 m) layer of sediments.

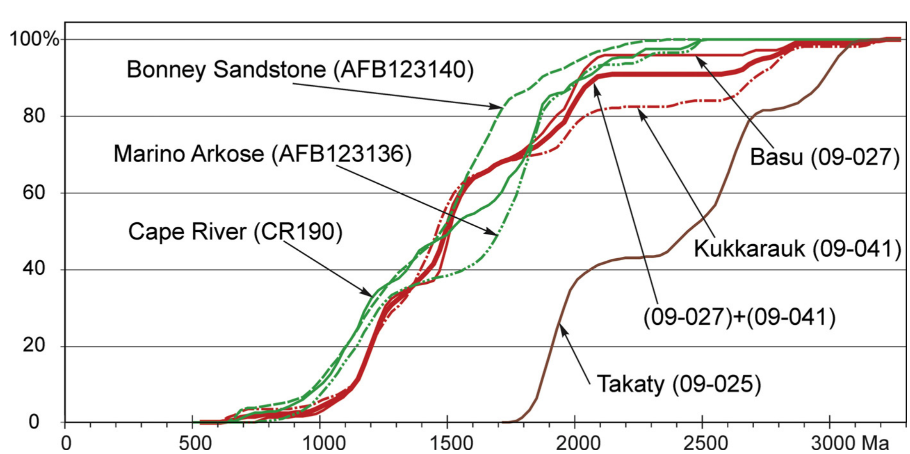

Fig. 6. Cumulative probability density plots for Australian Ediacaran-Cambrian age rocks, Ediacaran-Cambrian age samples from the Bashkirian Uplift and the Devonian Takaty Formation, Southern Urals.

The study of these exposures reveals several distinctive events in Sarmatia. They include crustal fragments with ages 3.8–2.9, 3.2–3.0 and ~2.7 Ga, sutured by orogenic belts with ages of 2.3–2.1 Ga (Samsonov et al., 1996; Shchipansky and Bogdanova, 1996; Chernyshov et al., 1997, 2001; Shcherbak et al., 1984, 2003, 2008; Bibikova et al., 2003, 2008a, 2010; Kirilyuk et al., 2002; Claesson et al., 2000, 2001, 2006; Gornostayev et al., 2004; Bogdanova, 2005; Shchipansky et al., 2007; Bogdanova et al., 2008; Lobach-Zhuchenko et al., 2005, 2010).

Volgo-Uralia is a large crustal domain that is entirely (excluding Taratsh uplift in the Urals) covered by a thick sediment cover. Nevertheless, many deep boreholes penetrate basement crystalline rocks. Geochronological studies on these core samples allow us to identify the age characteristics of the Volgo-Uralian complexes that range from 3.5 Ga (the oldest complexes exposed in the Taratash uplift) to 1.9 Ga. Within that range, there is a predominance of ages between 2.6 and 2.8 Ga (Sindern et al., 2005; Ronkin et al., 2007a,b; Bogdanova et al., 2008; Krasnobaev and Cherednichenko, 2005; Bibikova et al., 2008b, 2009).

It is worth emphasizing that ages between 2.4 and 2.2 Ga are not known from the northern part of EEP (Baltic/Fennoscandian shield) and they are extremely rare for the Volgo-Uralia and Sarmatia crustal blocks. Thus although the global LAME event (2.6–2.8 Ga; e.g. Condie, 2004) is widely observed across the EEP, the time interval 2.4–2.2 Ga is a time of tectonic and magmatic quiescence in the EEP.

The younger history of EEP is much better known on account of a more extensive geochronological data base. At ~2.1 Ga, the collision of Sarmatia and Volga-Uralia occurred and resulted in the Volgo-Sarmatian orogeny. As a result of this event, the Volga-Sarmatia (Sarmatia + Volga-Uralia) proto-craton was formed by ~2.00 Ga (Shchipansky et al., 2007; Bibikova et al., 2009; and references therein).

During post-collisional collapse of Volgo-Sarmatian orogen, voluminous production of 1.82–1.74 Ga plutons occurred including the Korosten (Amelin et al., 1994; Bogdanova et al., 2004; Shumlyanskyy et al., 2006) and Korsun'-Novomyrgorod (Kalinin, 2008; Starostenko et al., 2008) and Novoukrainskiy plutons consisting of gabbro-anorthosites-granites (Rapakivi-like granites). A large supra-subduction orogen (1.80–1.74 Ga) of the accretionary type with supra-subduction magmatism and metamorphism formed along the northwestern edge of Volgo-Sarmatia–the Osnitsk-Mikashevichi Igneous Belt (Aksamentova, 2002; Shchipansky et al., 2007; Bogdanova et al., 2008 and references therein). It was a precursor of the Volgo-Sarmatia and Fennoscandia collision zone.

At ~1.98–1.91 Ga, the Kola and Karelia blocks collided, forming the Kola-Karelian proto-craton and Lapland-Kola (sometimes named as Kola-Karelian) collisional orogen (Daly et al., 2006; Slabunov, 2008). Further crustal growth of Kola-Karelia is marked by the Fennian orogeny at ~ 1.89–1.87 Ga, the Svecobaltic orogeny at 1.84–1.80 Ga and the Nordic orogeny at 1.82–1.79 Ga, each of which accreted the older domains to each other and added juvenile crustal material so that the bulk of the Sveco-Fennian region was cratonised at ~1.8 Ga (Lahtinen et al., 2005). All tectonic/magmatic events resulted in the formation of Sveco-Fennia, and are collectively referred to as the Svecofennian orogeny. The Svecofennian orogeny evolved in stages, involving not only continent–continent collision and microcontinent accretion, but also large-scale extension of accreted crust and post-collisional gravitational collapse (Korja et al., 2006).

At ~1.8–1.75 Ga, Volgo-Sarmatia collided with Fennoscandia (Volyn–Middle-Russian collisional orogen; Bogdanova, 2005; Bogdanova et al., 2008 and references therein) to form Proto-Baltica. During collisional and post-collisional collapse of the Volyn–Middle-Russian collisional orogen, the emplacement of 1.70–1.45 Ga Rapakivi granite plutons and associated gabbro-anorthosites intrusions took place. The largest are the Salmi, Vyborg, Riga, Bornholm bodies (Neymark et al., 1994; Åhäll et al., 2000; Andersson et al., 2002; Bogdanova et al., 2008).

Proximal to the western margin of Proto-Baltica, numerous accretionary processes occurred intermittently between 1.7–0.9 Ga. These include the Gothian (1.73–1.55 Ga), the Telemarkian (1.52–1.48 Ga), the Danopolonian (1.47–1.42 Ga) and the Sveconorwegian (1.14–0.9 Ga). The latter Sveconorwegian orogeny is thought to be associated with global events in that same age range resulting in the formation of the supercontinent Rodinia (Bingen et al., 2008a,b; Bogdanova, 2005; Bogdanova et al., 2008; Meert and Torsvik, 2003; Pesonen et al., 2003; Li et al., 2008).

Source regions for the younger Neoproterozoic-Cambrian zircons (750–500 Ma) on the EEP exist along the northeastern periphery of the platform where relicts of the Pre-Uralides-Timanides orogeny compose the basement of the Pechora basin (Timan hills), western Polar Urals, the Kanin Peninsula and neighboring regions (Kuznetsov et al., 2006, 2007, 2010a). Analagous age ranges in the Cadomides are thought to be represented in the Pre-Caspian depression (Leonov et al., 2010).

Bimodal complexes of Volynia Large Igneous Province (western Ukraine, southern Belorussia and eastern Poland) are characterized by ages ~550 Ma (Shumlyansky et al., 2009; Shumlyansky and Nosova, 2008; Elming et al., 2007; Nawrocki et al., 2004). Recently, rhyolites from the Volynia area were dated (zircons, U-Pb, SHRIMP) as 557 ± 9 Ma (Nosova et al., 2010). The short-lived Volynia event produced thin (~several cm thick) tuffaceous layers that are traced in boreholes penetrating Ediacaran strata over the whole EEP from the Volynia region up to the Urals and White Sea region. In the western Middle Urals, the tuffaceous layers from the lowermost Chernykamen Fm. were dated (zircons, U-Pb, SHRIMP) as 557 ± 13 Ma (Maslov et al., 2006). The same tuffaceous layers from the ZimnieGory Fm. and Zimniy Bereg near the White Sea were dated as 555.4 ± 1.7 Ma (Martin et al., 2000) and 550 ± 4.4 Ma (Iglesia-Llanos et al., 2005). This narrow time interval ~(557–550 Ma) characterizes Baltica's Volynia LIP event and distinguishes it from the broad 750–500 Ma zircon populations that characterize the Pre-Uralides–Timanides (Kuznetsov et al., 2010a; Orlov et al., 2011; Soboleva et al., 2012).

Zircons with ages of ~400–490 Ma (Bingen and Solli, 2009; Bingen et al., 2009) can be found in complexes of the Scandinavian Caledonides located in the most northwestern part of EEP.

5. Provenance for the Asha Group sedimentary rocks

The sedimentary complexes located along the south Uralian periphery of the EEP are considered to be autochthonous or para-authochthonous with the EEP (i.e. Baltica or Proto-Baltica; Puchkov, 2000, 2010; Levashova et al., 2013). Given that relationship, it seems reasonable to assume that the principle source of clastic material into the Asha Group was derived from the Volga-Uralian region of the EEP immediately west of the Asha Group outcrops. This fragment of the basement comprises the Paleoproterozoic and Archean complexes spanning the range of about 3500–1750 Ma (Figs. 1 and 5). If this region is the source for the Asha Group, then it might be expected that the erosional products of crystalline complexes of Volgo-Uralia and relicts of orogens from its frame–Volgo-Sarmatian and Volyn-Middle-Russian (collectively called as "Volgo-Uralian provenance signal") should dominate. In contrast, the Asha Group sedimentary sequences reported in this study only about one third (32%) of the detrital zircons have ages reflecting Volgo-Uralia (3500–2100 Ma), complexes of Volgo-Sarmatian orogen (2100–2000 Ma) and Volyn-Middle-Russian orogen (2000–1750 Ma). Thus, the so-called "Volgo-Uralian" signature in the Asha Group rocks does not dominate the signal and indicates that alternative (and perhaps more distal) sources should also be considered.

The primary signal in the Asha Group gives ages ranging from 1750 to 900 Ma (66% of the grains studied). Sources adjacent to the Asha Group sediments with ages in this range are not known from Volgo-Uralia, but are known elsewhere in the EEP. Specifically, ages in this range are fairly common in the Sveconorwegian and Svecofennian areas some 2500 km from the Asha Group sedimentary basins. In principle, long-distant transport and reworking of detrital zircons is not unusual in modern settings. Therefore this northwestern Baltica signal implies the presence of a lengthy riverine system to deliver material to the peri-Baltic region where the Asha Group now resides. Although possible, the weak Volgo-Uralia (32%) signal compared to the dominant northwestern Baltic signal (66%) requires a river system eroding the Svecofennian and

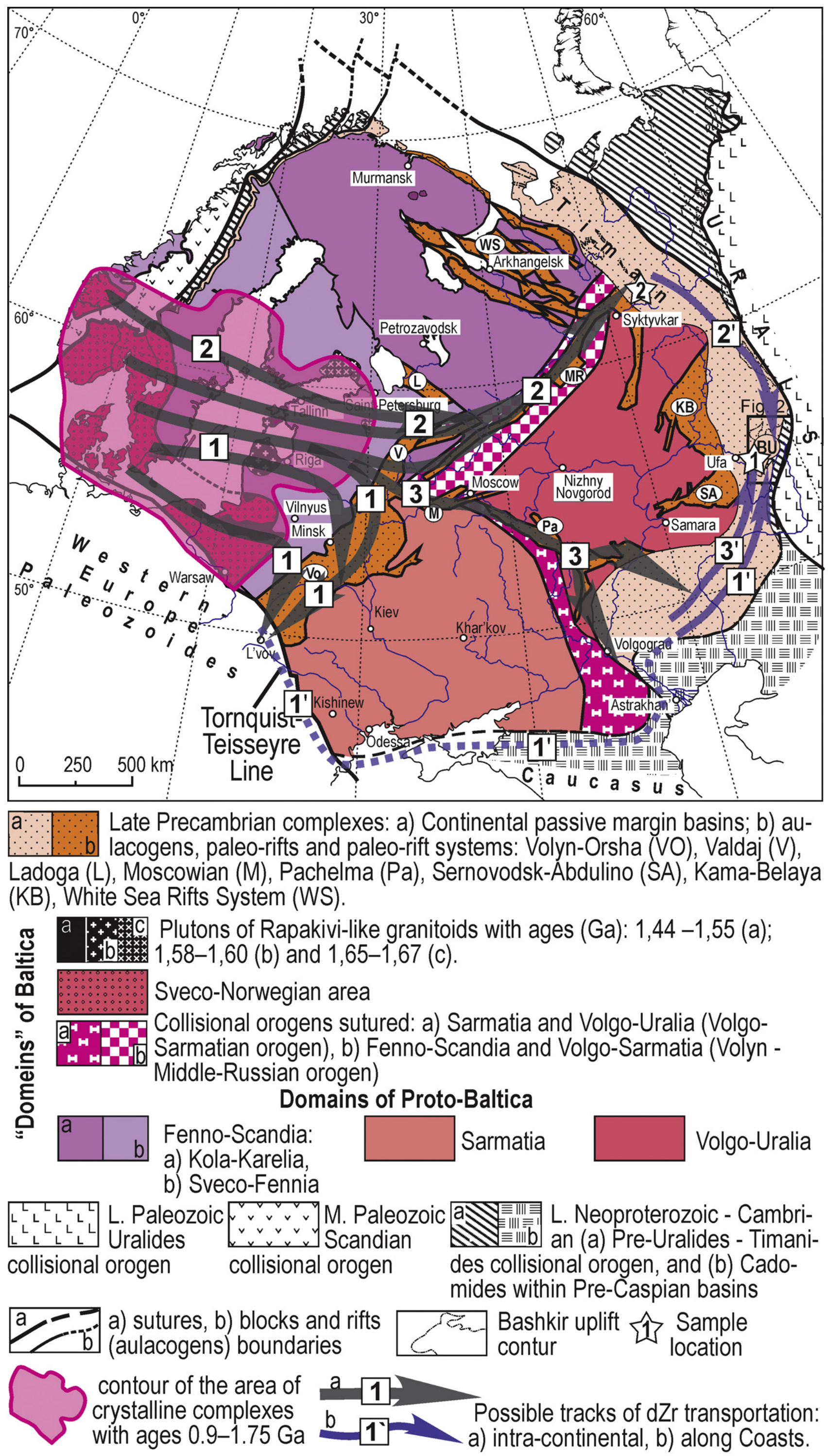

Fig. 7. Sediment transport and paleotopographical scheme for Baltica in the Ediacaran-Cambrian interval. Track 1 shows SW-transport directions, Track 2 shows transport directions toward the NE and Track 3 represents transport directions toward the present-day Caspian Sea.

Sveconorwegian regions with limited input or tributaries along the Volgo-Uralian margin.

Although there are modern analogs that might explain such a distribution, the paleotectonic setting in the region of the Asha Group during the Neoproterozoic seems at odds with a lengthy and mature river system. During the Neoproterozoic a series of SW-NE trending aulocogens in the Volhyn-Orsha region served as a paleodepression separating northwestern Baltica (i.e. Svecofennian and Sveconorwegian sources) from the region of the Asha Group (Kheraskova et al., 2001; Chamov, 2005; Chamov et al., 2010; Garetsky and Nagorniy, 2006; Bogdanova et al., 2008; Nikishin et al., 1996). Fig. 7 (Tracks 1, 2 and 3) show potential riverine systems that drained Baltica and delivered sediments to the southwest (Track 1), northeast (Track 2) and toward the Caspian region (Track 3).

Kuznetsov et al. (2010a,b) provided detrital zircon evidence that Svecofennian and Sveconorwegian areas were being diverted toward the Timanian margin of Baltica (Track 2, Fig. 7). Zircon ages from clastic rocks of the Djejim Formation (southern Timan) vary from ~2972 to 1175 Ma with a predominance of Paleoproterozoic ages. Kuznetsov et al. (2010a,b) argued that the majority of

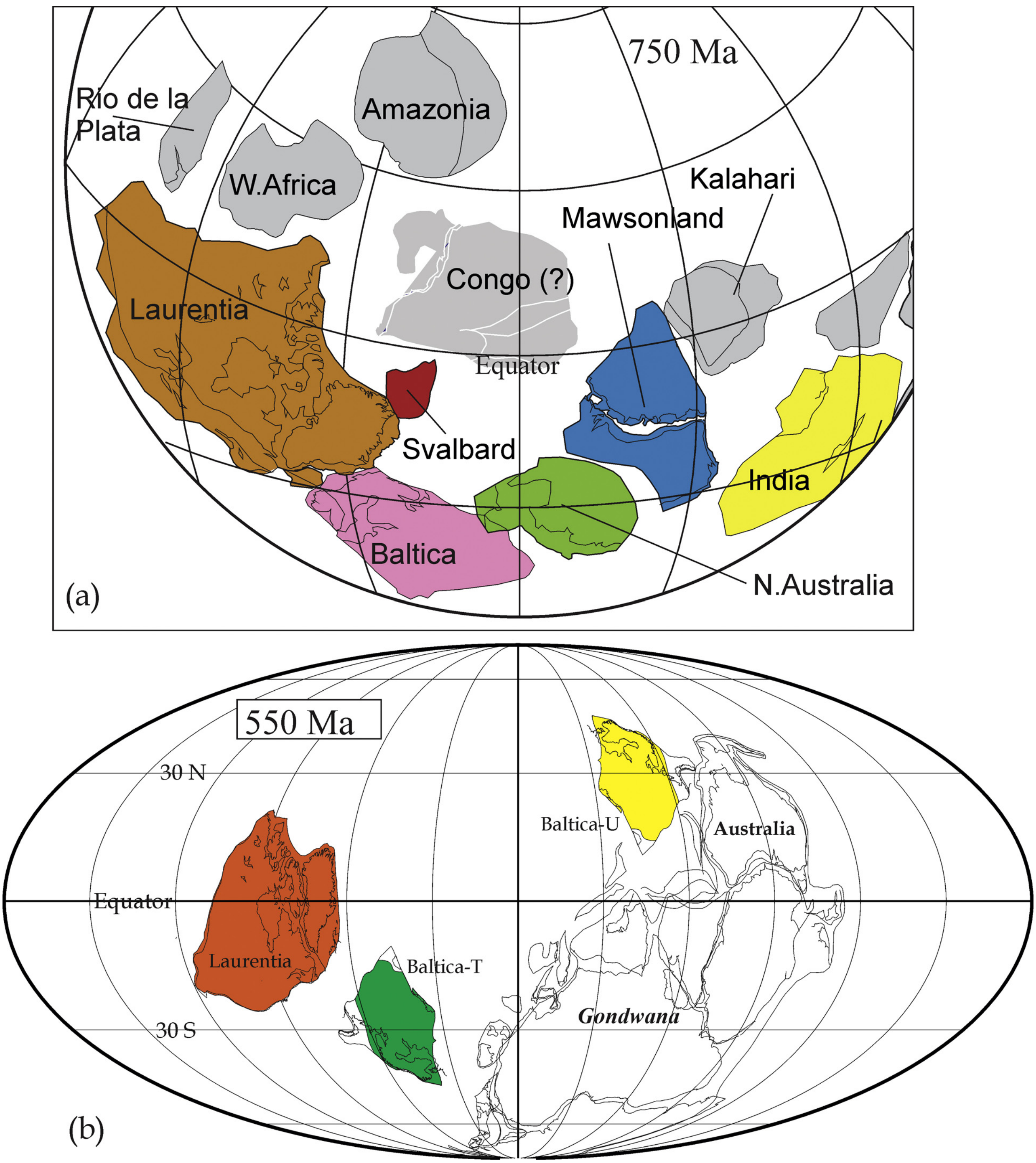

Fig. 8. (a) Adaptation of the paleotectonic reconstruction for Rodinia illustrating the so-called Australia Upside Down (AUD) hypothesis (after Evans, 2009; Swanson-Hysell et al., 2012). (b) Ediacaran reconstruction showing Baltica, Gondwana and Laurentia. Baltica is positioned between Laurentia and Gondwana (Baltica-T) using one polarity option and adjacent to Australia (Baltica-U) using the opposite polarity option. Sample locations: 1, Southern Urals, this paper; 2, Djejim Parma, Timan Hills (Kuznetsov et al., 2010a,b).

sediments in the Djejim Formation were derived from crystalline complexes located in the present-day central and northeastern parts of Baltica and to a lesser extent from northwestern Baltica. The proportions of far and weak 'northwestern Baltic' and near and strong 'central Baltica' signals in the Djejim detritus supports the presence of a physical barrier to transport.

Given the presence of these physical barriers to northwestern Baltic detritus into the Asha basin, it is possible that other modes of transport may have delivered this material into the Asha basin. One potential delivery mechanism is along-coast migration from the mouth areas of Volhyn-Orsha, Middle-Russian or Pachelma aulocogens that is difficult to test. A second possibility is that multiple cycles of erosion, deposition and transport served to concentrate the distal source signal. It is also possible that the so-called Svecofennian and Sveconorwegian detritus did not come from Baltica, but rather from another region that contains crustal elements of similar-age. This region may have been located adjacent to the Asha basin or from an 'unknown' easterly source with age characteristics similar to Sveconorwegian or Svecofennian rocks.

We examine the possibility of an alternate (or 'easterly' source) by examining the precursory paleogeography that ultimately culminated in the development of the Asha Basin. It is widely believed that a supercontinent called Rodinia persisted from ~1.1 Ga until 0.75 Ga, but the exact paleogeography of that supercontinent is contentious (Meert and Torsvik, 2003; Evans, 2009). In some reconstructions (Meert and Powell, 2001; Li et al., 2008), the Uralian margin of Baltica is depicted as a passive margin. Given the barriers to sedimentation discussed above, we argue that other models should be considered in order to explain the detrital zircon distribution in the Asha Group.

There are several alternatives to a Svecofennian/Sveconorwegian source for the Asha sediments that have appeared in the literature. Examples include positioning the Amazonian craton along strike from Baltica and adjacent to eastern Laurentia in the Rodinia configuration (e.g. Dalziel, 1997; Tohver et al., 2006) along with the West African craton adjacent to the Sarmatian margin of Baltica (Trompette, 1994; Johansson, 2009). A somewhat unconventional option is the Australia Upside Down (AUD option) proposed by Evans (2009). In the AUD configuration, the Queensland margin of Australia was juxtaposed with the Arctic or Uralian margin of Baltica at the beginning of the Neoproterozoic (Fig. 8a). A more recent discussion by Swanson-Hysell et al. (2012) showed that the AUD option does not contradict new paleomagnetic data from Neoproterozoic rocks in the Amadeus basin, Australia.

6. Australia Upside Down (AUD) and other options

In an effort to test the AUD configuration, we used the KS-test to compare the spectrum of detrital zircon ages from the Basu and Kukkarauk Formations to those from age-equivalent (Late Neoproterozoic) sedimentary rocks from eastern Australia. We examined the detrital zircon record from several Australian sandstone samples from the Cape River (CR190) quartz sandstone in Queensland (Late Cambrian age; Fergusson et al., 2007) along with the Marino arkosic sandstone (AFB123136) and Bonney sandstone (AFB123140; Ireland et al., 1998) from the Adelaide region. The Bonney sandstone (Wilpena Group) is Late Ediacaran in age and the Marino arkosic sandstone is thought to be of Marinoan age. We compared detrital zircon suites from the Australian samples to those found in the Asha Group.

The Australian samples are dominated by Mesoproterozoic-Late Paleoproterozoic ages with minor Neoproterozoic and Early Paleoproterozoic ages (Fig. 9). All three samples show peaks between 1.2 and 1.1 Ga, but vary somewhat in their Late Paleoproterozoic distributions. The KS-test showed cross-"p" values of 0.106, 0.884 and 0.363 (Table 1, Fig. 6) indicating that the Australian samples derived their zircons from similar regions.

The main difference between the Australian dataset and the Asha Group spectra is the lack of any Archean

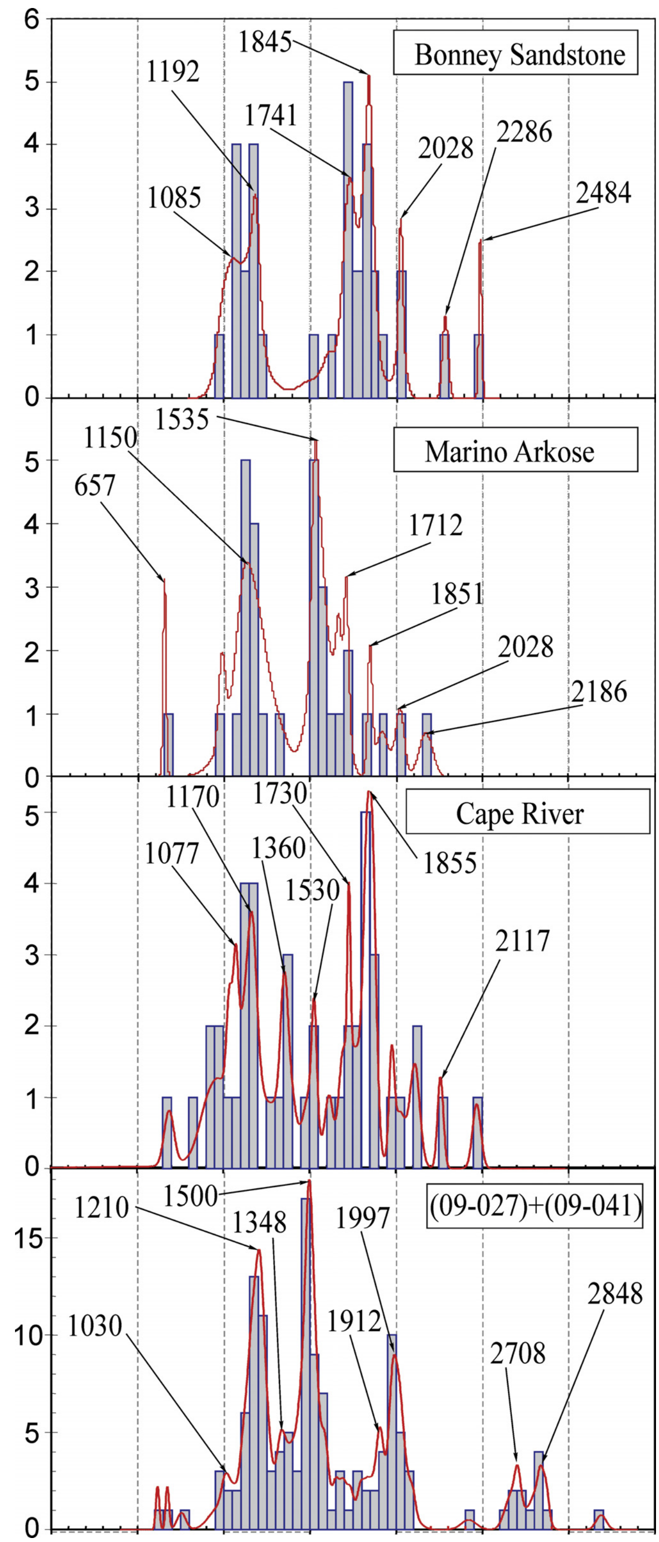

Fig. 9. Histogram for detrital zircon populations from the Bonney Sandstones, Marino Arkose (both Adelaide, south-eastern Australia; Ireland et al., 1998), the Cape River quartzite (Queensland, eastern Australia; Fergusson et al., 2007) and the Asha Group (09-027 + 09-041; this paper).

ages in the Australian samples. The Asha-Australia KS-test demonstrates a strong similarity between the two groups (Table 1). For example, for Cape River sample cross-"*p*" values rather, both for detrital zircons from the Basu Formation (09-207, $p = 0.654$), and Kukkarauk Formation (09-041, $p = 0.567$), and also for combined data set (09-207 + 09-041, $p = 0.573$).

The relatively strong correlation between the two datasets does not contradict a possible link between Australia and the eastern

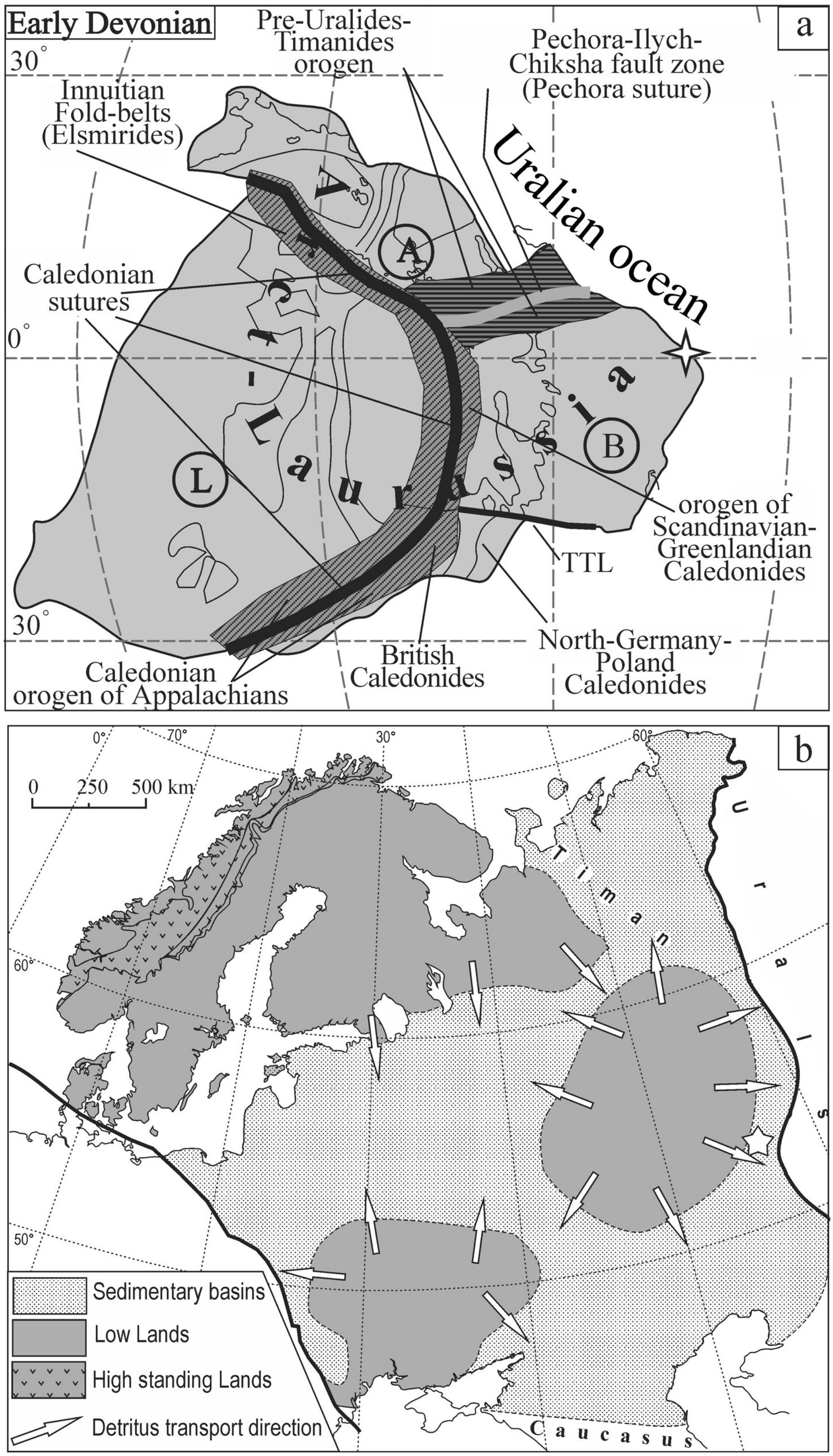

Fig. 10. (a) Conceptual tectonic setting of the Paleozoic-aged Baltica-Laurussia (modified after Kuznetsov et al., 2010a). TTL = Teisseyre-Tornquist Line, A = Arctida, B = Baltica, L = Laurentia. Latitude lines drawn every 30°. (b) Paleogeographic setting for the EEP during the Early Devonian.

margin of Baltica during the Neoproterozoic. Potential source regions include the central part of Australia (relicts of Musgrave orogeny 1400–1100 Ma), parts of the Northern Australia (relicts of Georgetown orogeny, 1750–1400 Ma; Giles et al., 2004; Betts and Giles, 2006) and/or more western parts of Australia.

Although the detrital zircon suites provide some evidence for an Australia-Baltica connection during the Neoproterozoic and/or Cambrian, the paleogeography for those time intervals is problematic. Assuming that Australia was the source of detritus for the Asha group sediments, then Australia (or parts of it) must have occupied space proximal to the Uralian margin of Baltica. The AUD hypothesis (Evans, 2009; Swanson-Hysell et al., 2012) is permissible using the extant Neoproterozoic paleomagnetic database (up to ~750 Ma). The AUD hypothesis is discussed in detail by both Evans (2009) and Swanson-Hysell et al. (2012), but neither publication offered a complete 'exit-strategy' for Australia into Gondwana. The Ediacaran paleogeography is no less problematic – especially for Baltica (see summary in Meert, 2013; Popov et al., 2002a,b, 2005; Meert et al., 1998, 2007; Iglesia-Llanos et al., 2005). Fig. 8b shows a possible reconstruction between Baltica at ~550 Ma using poles from the Winter Coast (Iglesia-Llanos et al., 2005; Popov et al., 2002a,b), Laurentia (Meert, 2014) and Gondwana (Meert, 2003). As with any paleomagnetic reconstruction, there are degrees of freedom in choice of polarity (i.e. north or south poles) and in longitude. In Fig. 8b, Baltica-T is positioned to the south of the present-day eastern margin of Laurentia and to the north of the African-South America join in Gondwana. This position is consistent with models that posit the opening of the Iapetus Ocean between Baltica and Laurentia beginning at ~615 Ma (Kamo et al., 1989; Puffer, 2002; Cawood and Nemchin, 2001; O'Brien and van der Pluijm, 2012). The position also results in relatively simple geometries and plate motions required to close the Iapetus, Theic and Rheic oceans between Baltica, Gondwana and Laurentia in the Paleozoic. In contrast, the Baltica-U option assumes the opposite polarity for the Baltica data and moves it longitudinally into a position adjacent to northwestern Australia. This reconstruction allows for detrital input from Australia to the Uralian margin and is consistent with the detrital zircon populations, but demands a very complex drift and rotation history for Baltica in the early Paleozoic that is not easily reconciled with the degrees of freedom allowed by paleomagnetic data or with key differences in tectonic setting and lithologies (Corkeron and George, 2001; Grey and Corkeron, 1998; Dow and Gemuts, 1969).

There is an alternative solution to the Ediacaran paleogeographic conundrum discussed above. If the AUD hypothesis is correct, then a significant amount of detrital input into the late Riphean-Early Vendian sequences of the Urals (from Australia) may have occurred before Australia began its journey toward Gondwana (i.e. early in the exit strategy). In this scenario, the detrital zircon populations observed in the Asha Group result from erosion, alongshore transport and re-working of the older sedimentary rocks along the Uralian margin rather than an Ediacaran-Cambrian juxtaposition of the Baltica and Australia. This hypothesis would require a detailed accounting of global paleogeographies from ~750 Ma to about 550 Ma that are currently lacking (Swanson-Hysell et al., 2012). A further test would be to examine detrital zircon populations of Riphean-Early Vendian rocks in the Urals to see if they contain the same populations as the Asha Group.

One additional possible source for the Asha Group sediments is that they were derived from the Amazonian-West African region. Detrital zircon records from modern West African rivers and the Amazon (Rino et al., 2008) have not been statistically evaluated with those of the Asha Group, but given the strong similarities between Baltica and Amazonia noted by Johansson (2009 and references therein) we feel it is premature to reject the 'archetypal' Rodinia setting in favor of the AUD hypothesis.

7. Provenance of the Devonian Takaty Formation

Deposition of the Takaty Formation in the Early Devonian occurred in a sedimentary basin along the Uralian margin of Baltica-Laurussia (Fig. 10a; Kuznetsov et al., 2010a). Evaluation of potential source regions for the Takaty Formation is complicated by the lack of any detritus younger than 1.86 Ga. This distribution would seemingly preclude both continental local sources as well as any arc-related complexes of Paleozoic age. Given the limited sample size (44 grains), we are cautious about making any definitive arguments about the source region for these clastic sediments.

8. Conclusions

(1) U/Pb-isotope dating (LA-ICP MS) of detrital zircons from sandstones of Basu and Kukkarauk Fm. from Asha Gr. and Takaty Fm of the western flank of the BU (Southern Urals) were carried out. Ages of detrital zircons from the Basu Formation fall within the time interval ~2900–700 Ma; from the Kukkarauk Fm from 3200 to 620 Ma and from the Takaty Formation from 3050 to 1850 Ma.
(2) Potential source regions for the Asha Group detrital zircons include the Eastern European platform, Australia and Amazonia.
(3) A comparison between the detrital zircon record of the Asha Series and detrital zircons from Australia show a strong correlation and therefore an Australian source cannot be ruled out. This conclusion is compatible with the Australia Upside Down hypothesis of Evans (2009) and Swanson-Hysell et al. (2012).
(4) Previous models of the Australia upside down hypothesis did not provide an 'exit' strategy for Australia's subsequent inclusion into Gondwana during the Ediacaran-Cambrian interval. Our analysis indicates that the 'exit' must have taken place earlier in the Neoproterozoic and most probably in the 700–750 Ma interval as an Ediacaran-Cambrian connection requires complex gyrations of Baltica and/or Australia in addition to incompatibilities in tectonic settings of the Urals and adjacent areas of Australia.
(5) Although sedimentary strata of the southwestern Urals including Basu, Kukkarauk and Takaty Fms. form a continuous-like section, the spectrum of detrital zircon ages within the Asha Group and Takaty Formation indicates major changes in basinal source and structure. The basin was most likely an intracontinental (intra-Rodinia) basin during the Tonian/Cryogenian interval and perhaps into the Ediacaran. Later, during accumulation of Takaty Fm. (Early Devonian), the basin formed along a passive margin with main input from the western side (EEP; Fig. 10b).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.09.011.

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