Provenance shift in Cambrian mid-Baltica: detrital zircon chronology of Ediacaran–Cambrian sandstones in Estonia

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Abstract. In order to clarify the tectono-sedimentary history of Paleozoic Baltica, age spectra of detrital zircon grains from the Ediacaran (Kotlin Regional Stage) and Lower Cambrian sandstones (lowermost Lontova and Lükati formations) in western Estonia in central Baltica were analyzed by LA-ICPMS. The abundant occurrence of Archean to Mesoproterozoic (2800–1000 Ma) zircon grains was confirmed in all samples. The new data provided the following information on the provenance of siliciclastic material as well as a major change in the sedimentary regime of the Paleo-Baltic basin during the Early Cambrian: (1) the Ediacaran–Lower Cambrian Paleo-Baltic basin received abundant terrigenous clastics from the core of Baltica underlain by the Archean–Mesoproterozoic crystalline crust, (2) the exposed surface area of the 1600 Ma Rapakivi granites apparently was more extensive during the Ediacaran–Early Cambrian than at present, (3) a major re-organization of the basin geometry occurred in the middle Early Cambrian (ca 530–515 Ma) in central Baltica, inducing a change in the sediment supply system, (4) in contrast to the total absence of Neoproterozoic detrital zircon grains before the middle Early Cambrian, their sudden appearance at this time, together with consistent occurrence at least until the mid-Devonian, suggests a significant uplift event located in southeast Baltica and/or in a more easterly land domain (e.g., in Sarmatia), (5) possible sources for the Neoproterozoic zircon grains include the peripheral mobile belts with pan-African signatures around Baltica, e.g., the so-called Gondwanan fragments along the Tornquist margin to the southwest and the Timanian belt along the northeastern margin.

Key words: Ediacaran, Cambrian, Baltica, detrital zircon, U–Pb age, provenance, Rapakivi.

INTRODUCTION

Baltica, one of the major continental blocks during the Paleozoic, remained isolated after its Neoproterozoic detachment from Rodinia until its collision with Laurentia during the Silurian–Devonian. In this context, detrital zircon chronology appears to be a promising tool for provenance analysis of Baltic sedimentary basins. Some preliminary attempts have already been made mostly for the peripheral orogenic belts around Baltica (e.g., Valverde-Vaquero et al. 2000; Nawrocki & Poprawa 2006; Cawood et al. 2007; Kuznetsov et al. 2010). In contrast, studies on the interior of Baltica were rather few, probably because it appeared obvious that the sub-unconformity Precambrian basement rocks, currently exposed in central Baltica, are the main source for the thick succession of Lower Paleozoic siliciclastic sedimentary rocks. Nonetheless, some attempts at provenance analysis were recently made for the Lower–Middle Paleozoic sandstones in east-central Baltica (e.g., Kuznetsov et al. 2011; Miller et al. 2011; Põldvere et al. 2014). As for the Baltica core area in Estonia, Põldvere et al. (2014) lately reported for the first time age spectra of detrital zircons from Cambrian and Devonian sandstones and confirmed that the Early Paleozoic siliciclastics clearly reflected the Precambrian basement geology of Baltica. On the other hand, the Cambrian basin studies on a regional scale (e.g., Mens & Pirrus 1997; Nielsen & Schovsbo 2011) suggest that a major change in basin geometry has occurred during the Early Cambrian in central Baltica.

It is worth testing whether this putative change in regional basin geometry could be indeed reflected in the detrital zircon population from Paleozoic sandstones of the mid-Baltic area. In order to compare the age spectra of detrital zircon from sandstones, particularly of pre-Early Cambrian and of post-Cambrian intervals, we dated detrital zircon grains obtained from the Ediacaran and Lower Cambrian (Stage 2; early Tommotian) sandstones of central Baltica. This article reports age spectra of detrital zircon in sandstones from the Ediacaran Kotlin Regional Stage and the Lower Cambrian Lontova and Lükati formations in western Estonia and discusses their geological implications.

GEOLOGIC SETTING

The pre-Quaternary surface crust of Estonia is composed of non-metamorphosed, scarcely deformed Ediacaran to Middle Paleozoic shallow marine siliciclastics and carbonates (e.g., Raukas & Teedumäe 1997; Fig. 1). Most of the Ediacaran–Lower Cambrian strata occur in the subsurface, except for the upper part of the Lower Cambrian, which is remarkably exposed along a coastal cliff (Baltic klint) on the Gulf of Finland in northern Estonia. Numerous drillcores, however, confirm the subsurface presence of siltstone/sandstone-dominant Ediacaran rocks (Kotlin Regional Stage) overlain by the Lower Cambrian Lontova and Lükati formations. These strata rest unconformably upon the Precambrian gneisses and granites.

SAMPLES

This study utilized three sandstone samples from the Velise F-97 drillcore in central Estonia (Fig. 1). Sample VKT is from the uppermost Ediacaran Kotlin Regional Stage, recovered at a depth of 354 m of the Velise F-97 core, whereas samples VLN and VLK come from the lowermost Lontova Formation (at 340 m depth) and the Lükati Formation (at 285 m depth), respectively. The age of the Kotlin sandstone is rather loosely constrained (<570 Ma), whereas the Lontova Formation is represented by the sub-trilobitic acritarch assemblage of *Asteridium tornatum–C. velvetum* that is likely correlated with the lower–middle part of the Cambrian Stage 2 (or early Tommotian in Siberia; ca 529–523? Ma). Note that the overlying Lükati Formation and the lowermost Tiskre Formation (a sandstone sample from the Kakumägi Member was lately analyzed by Põldvere et al. 2014) belong to the second oldest trilobite zone of *Schmidtiellus mickwitzi*, which is correlated with the middle part of the Cambrian Stage 3 (or Atdabanian in Siberia; ca 521–513? Ma).

The sampled sandstones are light grey, very fine-grained, weakly cemented arenite, mostly dominated by quartz grains. The details of separation and dating procedures are described as "Analytical procedures" in Data Depository at http://dx.doi.org/10.15152/GEO.5

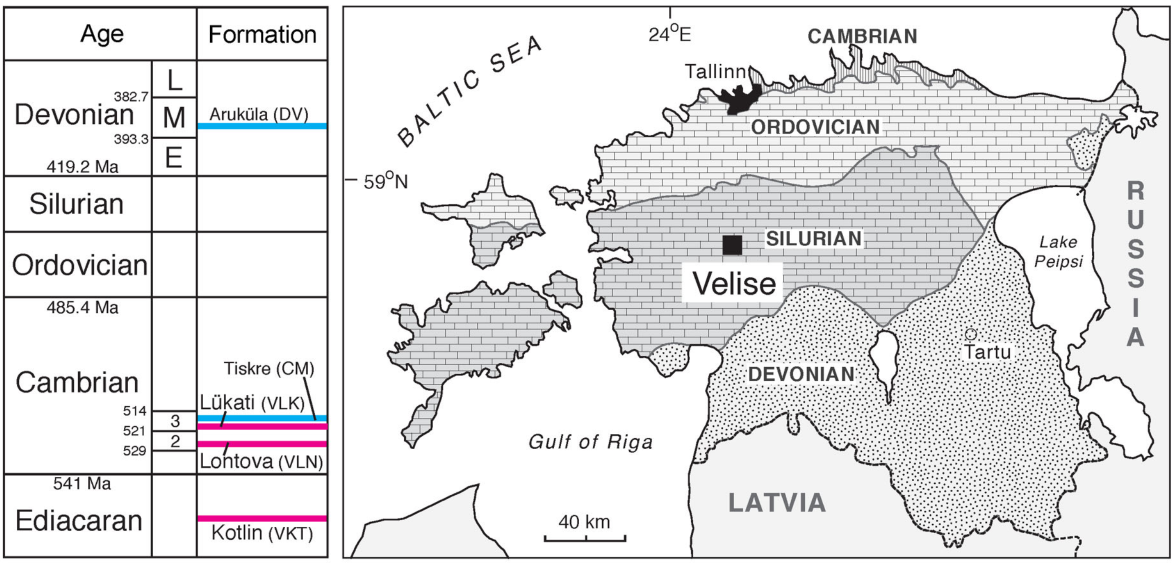


Fig. 1. Ediacaran to Middle Paleozoic stratigraphy in western Estonia with horizons discussed in this article and the location of the Velise-F97 drilling site on a simplified geologic map of Estonia (simplified from Raukas & Teedumäe 1997; Nielsen & Schovsbo 2011). Strata of the sandstones analyzed in this study are shown in red and those of Põldvere et al. (2014) in blue.

RESULTS

Figure 2 summarizes the $^{206}Pb/^{238}U$ age populations of the detrital zircon grains from samples VKT, VLN and VLK. Data are plotted as histograms with probability age frequency curves. All figures use only age data plotted on the concordia line. Tables of measurements and concordia diagrams of the analyzed samples are stored in DD-Tables 1–3 and DD-Figs 1–3 in the data depository (http://dx.doi.org/10.15152/GEO.5). For comparison, Fig. 2 also displays the results by Põldvere et al. (2014) on the same scale.

It is clear that samples VKT and VLN share an almost identical zircon age spectrum, which is characterized by three distinct age groups; i.e. 2900 Ma (Mesoarchean), 2000–1700 Ma (Paleoproterozoic) and 1650–1300 Ma (mostly Mesoproterozoic). In particular, the dominance of Mesoproterozoic grains is noteworthy, as they form a sharp peak at ca 1600 Ma (the beginning of the Mesoproterozoic) in both samples. On the other hand, sample VLK shows a sharp contrast with samples VKT and VLN in zircon chronology; on the contrary, its spectrum is similar to those of the Cambrian Tiskre (CM) and Devonian Aruküla (DV) formations from Estonia (Põldvere et al. 2014) that lack the prominent peak at 1600 Ma, and instead display several age fractions earlier than 1200 Ma.

DISCUSSION

Reflection of the Precambrian basement with prominent Rapakivi signature

The similarity in the age spectrum between samples VKT and VLN (Fig. 2) points to the following: (1) the Ediacaran to earliest Cambrian sedimentary basin of central Baltica had a provenance that essentially corresponds to the Precambrian basement rocks currently exposed in Baltica and (2) this provenance-basin setting did not change for nearly 50 million years from the Ediacaran to earliest Cambrian.

The oldest zircon grains of ca 2900–2800 Ma from both samples obviously correspond in age to the Archean rocks of the Kola–Karelian block in northeast Baltica (Lehtinen et al. 2005). Likewise, the grains of the late Paleoproterozoic ages (2000–1800 Ma) were likely derived from the unique Svecofennian orogen in central Baltica and those of early Mesoproterozoic ages (1650–1500 Ma) from the Rapakivi granites. As to the Archean and Mesoproterozoic zircon age, the present data together with those by Põldvere et al. (2014) are in good agreement with recent paleogeographic reconstruction (e.g. Mens & Pirrus 1997).

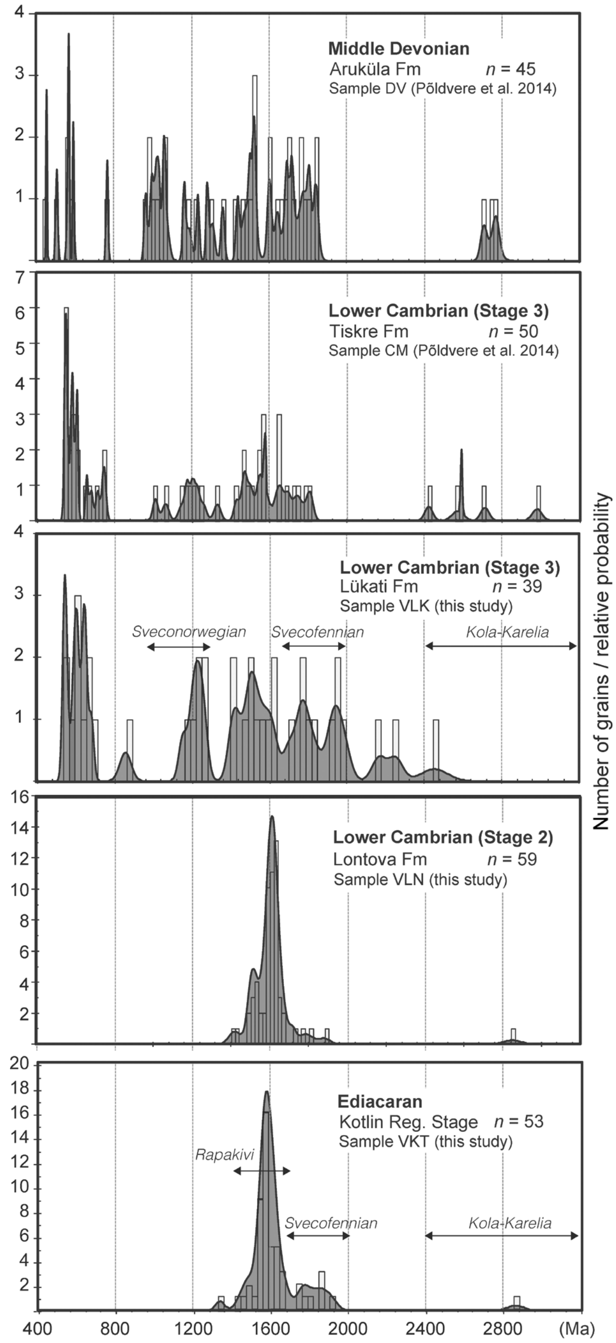


Fig. 2. U–Pb age spectra (in the histogram and in the probability age frequency curve) of detrital zircon grains from the Ediacaran Kotlin Regional Stage (VKT), Lower Cambrian (Stage 2) Lontova and Lükati formations (VLN, VLK) of the Velise-F97 drilled core from central Estonia, demonstrated together with those of the Lower Cambrian (Stage 3) Tiskre Formation (CM) and the Middle Devonian Aruküla Formation (DV) (Põldvere et al. 2014) for comparison. Refer to http://dx.doi.org/10.15152/GEO.5 for measurement tables (DD-Tables 1–3) and Concordia diagrams (DD-Figs 1–3). One time bin for histogram is 20 million years.

The sedimentary records of the Lower Cambrian in Baltica suggest that the birth and development of the mid-Baltic sedimentary basin was controlled mostly by late Neoproterozoic rifting (Fig. 3A; Nielsen & Schovsbo 2011). For the northern margin of the main Paleo-Baltic basin with an east-facing slope (corresponding to modern Estonia), siliciclastic material was delivered mostly from the northern and western parts of the basin, i.e. from the central Fennoscandian shield. In particular, the prominent peak of zircon grains at 1650–1500 Ma is noteworthy because these ages, similar to the Rapakivi age, suggest that this unique alkaline granitic suite was exposed in the central Baltic to a much wider extent during the Ediacaran and earliest Cambrian than at present.

Change in the Early Cambrian and subsequent quiescence

All five analyzed sandstone samples from Estonia share more or less the same Archean to Mesoproterozoic signatures even with the consistent absence in the Early Paleoproterozoic ages of 2400–2000 Ma (Fig. 2), although the dominance of around 1600 Ma Rapakivi ages was considerably suppressed in the Lower Cambrian Lükati/Tiskre (VLK and CM) and mid-Devonian Aruküla (DV) samples. Nonetheless, the most striking difference exists in the content of Neoproterozoic zircon grains between the Ediacaran–lowermost Cambrian (VKT and VLN) sandstones and the latter three (VLK, CM and DV). The appearance and consistent occurrence of 1300–900 Ma zircon grains in the Lower Cambrian and younger sandstones probably reflect the uplift–exposure of the Mesoproterozoic Sveconorwegian orogen due to the Caledonian orogeny (Cambrian–Devonian, ca 500–400 Ma) along the northwestern margin of Baltica (e.g., McKerrow et al. 2000).

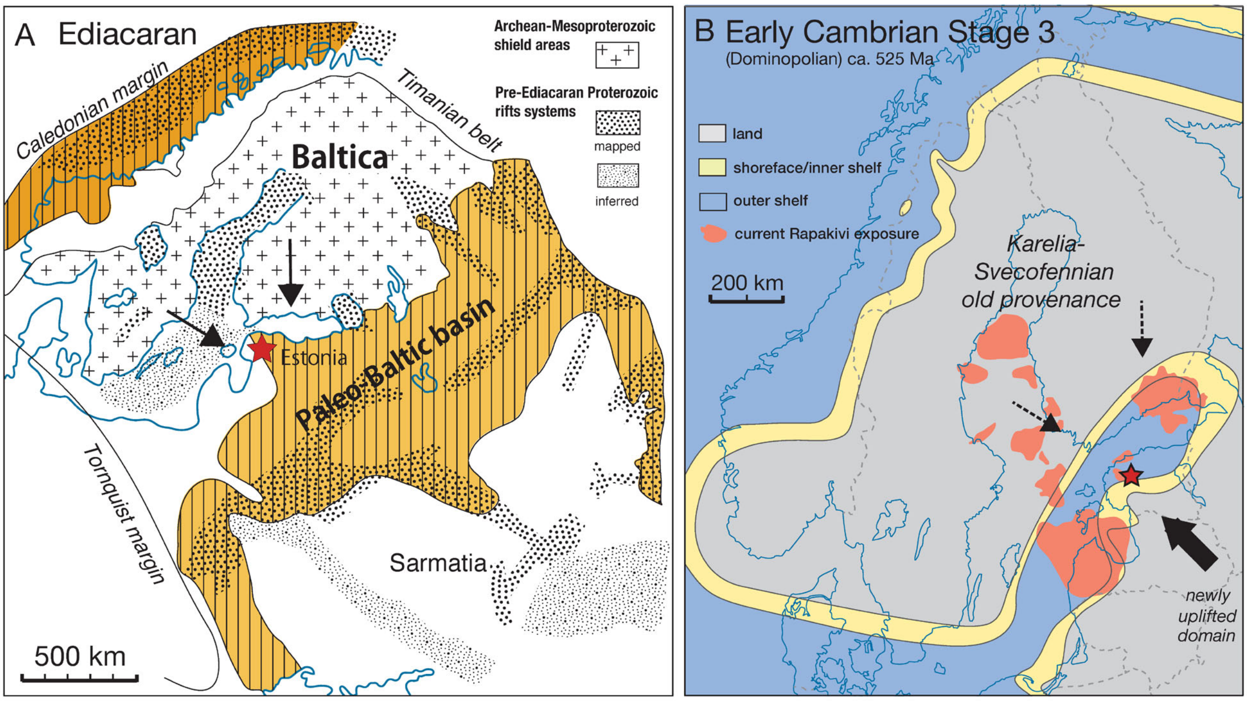
Similarly to the Ediacaran–earliest Cambrian interval, the Paleo-Baltic basin consistently maintained the same terrigenous provenance for more than 130 m.y. from the Early Cambrian (ca 520–515 Ma) to mid-Devonian (ca 390 Ma). In other words, there is no significant sedimentological indication for multiple tectonic/geologic events previously known in and around Baltica during this interval, such as the collision/amalgamation of Cadomian–Avalonian blocks (Ordovician–Devonian, ca 450–400 Ma) along the southern margin, asteroid impact (mid-Ordovician, ca 467 Ma) and large-scale eustatic sea-level changes, including the end-Ordovician glacial regression (ca 445 Ma) (e.g., Schmitz et al. 2003; Delabroye & Vecoli 2010; Linnemann et al. 2012). Instead, the Paleo-Baltic basin and its provenance areas were likely rather stable throughout most of the Early Paleozoic, except for just one conspicuous change in the middle Early Cambrian sedimentary regime recorded in its central part.

As to the sharp contrast in zircon age spectra between the Ediacaran/lowermost Cambrian sandstones (VKT, VLN) and the Lower Cambrian/mid-Devonian (VLK, CM and DV) samples (Fig. 2), there is an independent line of evidence that concordantly suggests a significant major change in basin geometry during the Early Cambrian. Nielsen & Schobsvo (2011) documented that a new mid-continent depression developed in the Early Cambrian as an NNE-trending narrow basin opened to the south, and that this event has totally changed the sedimentary regime in the central part of the Paleo-Baltic basin (Fig. 3B). According to their reconstructed paleogeographic map, the domain corresponding to present-day Estonia likely started to receive terrigenous clastics not only from the core of Baltica in the north/west, as was the case during the Ediacaran, but also from uplifted areas in the east/southeast since the Early Cambrian appearance of this embayment. The detrital zircon data from the Estonian sandstones (Põldvere et al. 2014; present study) fully agree with the claimed change in the Cambrian Paleo-Baltic basin geometry. In the east-neighboring area near St Petersburg, east Russia, similar age spectra of detrital zircon were lately reported from the Middle Cambrian, Ordovician and Devonian (but not Lower Cambrian and Ediacaran) sandstones (Kuznetsov et al. 2011; Miller et al. 2011), which are almost identical to those of the Tiskre and Aruküla sandstones. Although no data were provided for the Ediacaran and lowermost Cambrian, their data are in good accordance with the present conclusion.

This change in the Paleo-Baltic basin geometry in response to the modification of provenance areas marked not only the main tectonic episode in the Cambrian but also the greatest re-organization of the sedimentary setting for the Paleo-Baltic basin. Particularly noteworthy is the narrow time window for this change, occurring between the middle Epoch 2 and early Epoch 3 in the Early Cambrian, i.e., 5–10 m.y. (Fig. 1). Nonetheless possible cause(s) responsible for the Early Cambrian regional uplift in the eastern Baltica (Fig. 3C) still remains unknown.

Emergence of a new easterly provenance area

The present result points out an unsolved issue relevant to the newly emerged terrigenous source to the east; i.e., eastern Baltica and/or further easterly domain called Sarmatia in the East European craton (EEC) (Fig. 3C). Baltica (or Fennoscandian) and Sarmatia in the EEC are composed of Archean to Early Neoproterozoic crystalline basement rocks without Middle–Late Neoproteorozoic rocks (e.g., Gee & Stephenson 2006). Thus the relatively



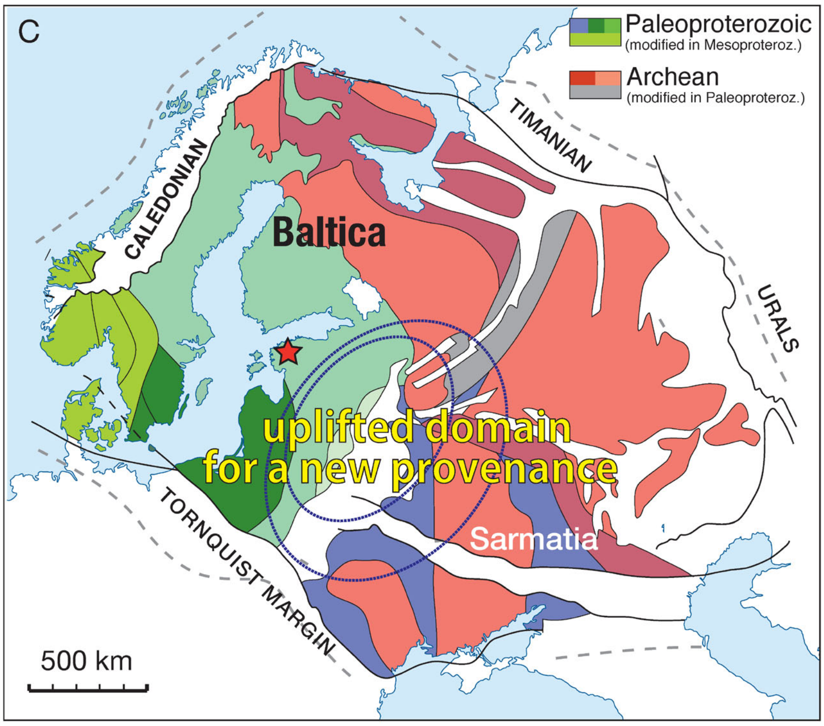


Fig. 3. Paleogeographic maps of the Ediacaran and Early Cambrian Baltica (A, B) and the basement geotectonic map of East European Craton (EEC). **A**, the Paleo-Baltic basin development immediately after the Ediacaran rifting; **B**, the same basin in the Early Cambrian (Stage 3 or Dominopolian) with the current distribution of the Rapakivi granitic suite (after Lehtinen et al. 2005 and Nielsen & Schovsbo 2011). Note the change in the terrigenous clastic supply system; **C**, major Archean–Proterozoic units of the EEC (simplified from Gee & Stephenson 2006). The appearance of an uplifted domain and resultant onset of westward terrigenous flux in the southeastern EEC is suggested but there is no known candidate with the Neoproterozoic crust of Pan-African age.

younger 750–550 Ma (Late Neoproterozoic) zircon grains in the Cambrian and Devonian sandstones in Estonia were obviously derived neither from the core of Baltica nor from Sarmatia but more likely from the peripheral orogenic belts around the EEC.

Possible candidates for the 750–550 Ma grain source include the Timanian–Pechora belt along the modern northeastern margin of Baltica and the so-called Gondwanan fragments along the Tornquist front along the southwest (Fig. 3C). Kuznetzov et al. (2011) proposed that the Neoproterozoic grains in the Cambrian to Devonian sandstones in the St Petersburg area were all derived from the Timanian belt. For providing terrigenous clastics to Paleozoic Estonia, however, the Timanian margin appears too far to the north and mostly too young to supply abundant 750 Ma zircon grains.

In contrast, present authors have emphasized a possible supply from Gondwanan fragments with unique Pan-African (or Pan-Gondwanan) signatures (Põldvere et al. 2014), such as the Avalonian–Cadomian blocks stigmatized with the late Neoproterozoic Pan-African magmatism/metamorphism. In general, the tectonic interaction between Baltica and the Avalonian–Cadomian blocks along the Tornquist margin is regarded to have started in the end-Ordovician (e.g., Torsvik & Cocks 2013), as well as for the case of the Brabant massif (Linnemann et al. 2012). Nonetheless, much earlier tectono-sedimentary interaction between the Gondwanan fragments and Baltica during the Early Cambrian appears possible, by assuming another unidentified fragment of Gondwanan further east of Cadomian blocks. The present preliminary results emphasize that further investigations are definitely needed for reconstructing the whole tectono-sedimentary history of the Neoproterozoic to early Paleozoic Baltica.

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