Article

Not peer-reviewed version

Detrital Zircon Geochronology of the Volyn-Orsha Sedimentary Basin in Western Ukraine: Implications for the Meso-Neoproterozoic History of Baltica and Possible Link to Amazonia and the Grenvillian – Sveconorwegian – Sunsas Orogenic Belt

Leonid Shumlyanskyy * , Andrey Bekker , Iryna Tarasko , Ion Francovschi , Simon A. Wilde , Victor Melnychuk

Posted Date: 30 March 2023

doi: 10.20944/preprints202303.0518.v1

Keywords: Mesoproterozoic; Neoproterozoic; Baltica; Amazonia; detrital zircon; Volyn-Orsha basin

Article

Detrital Zircon Geochronology of the Volyn-Orsha Sedimentary Basin in Western Ukraine: Implications for the Meso-Neoproterozoic History of Baltica and Possible Link to Amazonia and the Grenvillian—Sveconorwegian—Sunsas Orogenic Belt

Leonid Shumlyanskyy [1,2,*], Andrey Bekker [3,4], Iryna Tarasko [5], Ion Francovschi [6,7], Simon A. Wilde [1] and Viktor Melnychuk [8]

[1] School of Earth and Planetary Sciences, Curtin University, Perth, GPO Box U1987, WA 6845, Australia; Leonid.Shumlyanskyy@curtin.edu.au; s.wilde@curtin.edu.au
[2] Institute of Geological Sciences, Polish Academy of Sciences (ING PAN), Research Centre in Kraków, Senacka 1, PL–31002 Kraków, Poland
[3] Department of Earth & Planetary Sciences, University of California, Riverside, CA 92521, USA; andreyb@ucr.edu
[4] Department of Geology, University of Johannesburg, Auckland Park 2006, South Africa
[5] Rivne Complex Geological Enterprise of the State Ukrainian Geological Company, Stelmakha 11, 33000, Rivne, Ukraine; sergeolvol@gmail.com
[6] The University of Bucharest, Faculty of Geology and Geophysics, Bucharest, Romania; frankovski.ww@gmail.com
[7] Institute of Geology and Seismology, Chișinău, Republic of Moldova
[8] The National University of Water and Environmental Engineering, Rivne, Ukraine; v.g.melnychuk@nuwm.edu.ua
* Correspondence: Leonid.Shumlyanskyy@curtin.edu.au.

Abstract: We used LA-ICP-MS U-Pb data for detrital zircon to constrain the Maximum Depositional Age (MDA) and provenance of clastic sedimentary rocks of the Volyn-Orsha sedimentary basin, which filled an elongated (~625×250 km) depression in SW Baltica and attained ~900 m in thickness. Eighty-six zircons out of one hundred and three yielded concordant dates, with most of them (86 %) falling in the time interval between 1655 ± 3 and 1044 ± 16 Ma and clustering in two peaks at ca. 1630 and 1230 Ma. The remaining zircons yielded dates older than 1800 Ma. The MDA is defined by a tight group of three zircons with a weighted average age of 1079 ± 8 Ma. This age corresponds to the time of a clockwise ~90° rotation of Baltica and the formation of the Grenvillian – Sveconorwegian – Sunsas orogenic belts. Subsidence was facilitated by the presence of eclogites derived from subducted oceanic crust. The sediments of the Orsha sub-basin in the northeastern part of the basin were derived from the local crystalline basement, whereas the sediments in the Volyn sub-basin, extending to the margin of Baltica, were transported from the orogen between Laurentia, Baltica, and Amazonia.

Keywords: Mesoproterozoic; Neoproterozoic; Baltica; Amazonia; detrital zircon; Volyn-Orsha basin

1. Introduction

For Precambrian sedimentary successions that do not bear paleontological records or lack datable authigenic minerals and volcanogenic rocks, dating of detrital minerals represents a useful tool for assessing the Maximum Depositional Age (MDA). Due to its high physical robustness and ability to survive long transportation, detrital zircon is widely used to assess the provenance of clastic sedimentary material and provide an estimate of the timing of deposition [1,2]. The zircon record can also be used to define the tectonic setting of sedimentary basins [3,4], and to investigate crustal evolution [5–10].

 doi:10.20944/preprints202303.0518.v1

During the Mesoproterozoic and early Neoproterozoic, most parts of Baltica (also known as the East European platform) experienced a tectonically quiet regime that was accompanied by denudation; it was episodically interrupted by localized intraplate anorthosite-mangerite-charnockite-granite (AMCG) magmatism [11,12]. Orogenic processes in these times were manifested in the Transscandinavian igneous belt (ca. 1810-1650 Ma; [13,14]) and the Sveconorvegian orogenic belt (ca. 1140-960 Ma; [15,16]), located in the extreme NW part of Baltica. Despite a generally stable tectonic regime that dominated Baltica during the Mesoproterozoic to the beginning of the Neoproterozoic, a series of sedimentary basins developed [11,17,18]. One such system, known as the Volyn-Middle Russia, extends from SW to NE across the whole of Baltica for a distance of over 2000 km, and includes the Volyn-Orsha basin and Middle Russian – Moscow – Valdai (Krestsy) aulacogen [19]. At the SW margin of Baltica, the system is abruptly terminated by the Trans-European Suture Zone. The Pachelma aulacogen is another example of this system of sedimentary basins, and strikes nearly perpendicular to the Volyn-Middle Russia system (Figure 1).

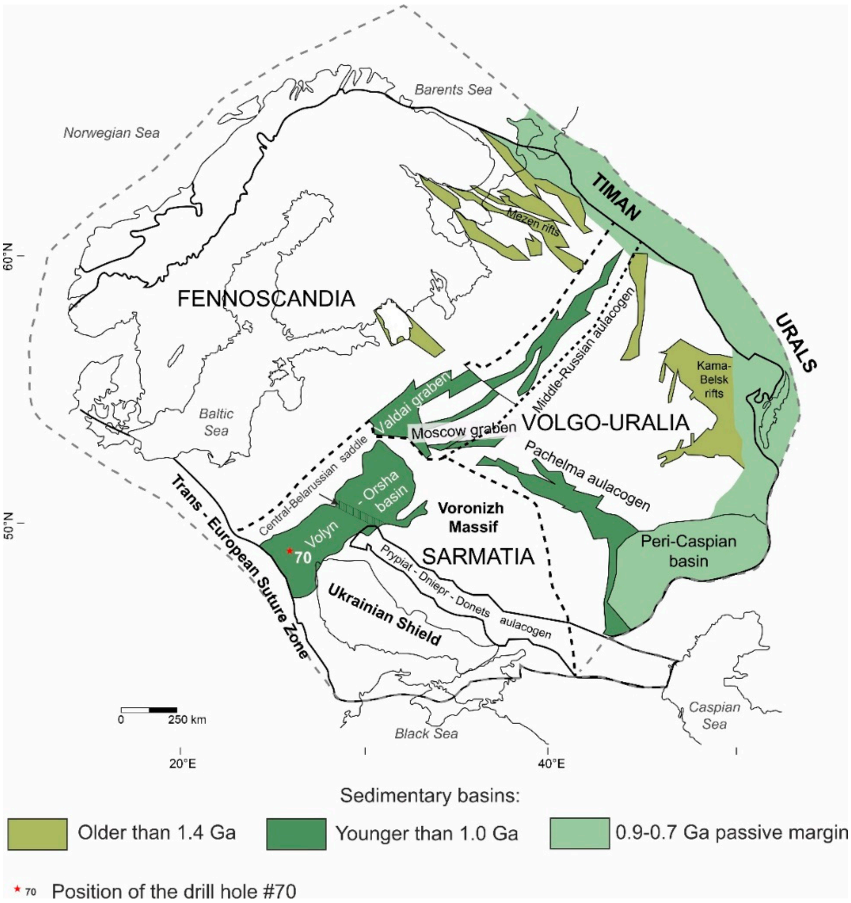

Figure 1. Meso- and Neoproterozoic sedimentary basins in Baltica, modified after [11]. The Volyn-Middle Russia System, together with the Pachelma aulacogen, generally follow the Paleoproterozoic suture zones separating the main Archean and early Paleoproterozoic crustal blocks composing Baltica.

It has long been recognized that the Volyn-Middle Russia system of sedimentary basins and the Pachelma aulacogen broadly developed along the suture zones between the main crustal segments constituting Baltica, i.e., Sarmatia, Fennoscandia and Volgo-Uralia (Figure 1) [19–21]. This relationship between the late Stenian - early Tonian sedimentary basins and Paleoproterozoic suture zones is considered not to be accidental. Other important features of the Volyn-Orsha basin include its amagmatic nature, lack of well-defined rift boundaries, and low heat flow [20].

There is no consensus on the tectonic evolution of the Volyn-Middle Russia sedimentary system and its relationships with other Meso-Neoproterozoic sedimentary basins in Baltica. Some researchers consider the entire Volyn-Middle Russia system as a single tectonic structure, while others stress the independent and non-synchronous evolution of its different parts (see discussion in [19]). The main unresolved problem is the poorly-known depositional age of the sedimentary basins and the tectonic mechanism for their formation. In this short communication, we present new detrital zircons dates for sandstones of the Polissya Group in the Volyn-Orsha basin. These data are further used to discuss the sedimentary provenance, the possible link with Amazonia, and the maximum depositional age of the Polissya Group to infer the possible drivers for the basin initiation.

2. The Volyn-Orsha sedimentary basin

The Volyn-Orsha basin represents the western part of the Volyn-Middle Russia basin system (Figure 1). In general, this basin system is amagmatic. The Polissya Group is cut by several sill-like bodies that were previously dated by the K-Ar whole-rock method at ca. 1200-1050 Ma [22]. However, recent studies have shown their affinity to the Neoproterozoic Volyn flood basalt province (see below). Similarly, an intrusive dolerite body in the Valdai (Krestsy) graben yielded a Mesoproterozoic K-Ar age of 1345-1180 Ma [23].

Terrigenous rocks prevail in the sedimentary basin system. In the Moscow graben (Figure 1), continental red beds dominate a 500 m thick sequence of alternating gravelly arkoses, mudstones, and siltstones [11]. The upper part of the sequence is composed of brown mudstones with lenses of siltstone and sandstone, as well as limestone. The Valdai (Krestsy) graben is filled with ~300 m of thick red, terrigenous, siliciclastic rocks, whereas in the Middle-Russian Rift System, the thickness of the terrigenous red-bed sediments reaches approximately 1500 m [18]. The Pachelma aulacogen contains 700 m of variegated, poorly sorted, coarse- to medium-grained arkosic sandstones, conglomerates, siltstones, and mudstones, overlying unconformably basal, quartz-rich sandstones. Geophysical data indicate that the total thickness of sediments may exceed 4 km [24].

The Volyn-Orsha basin is located in the SW part of Baltica. It is an elongated sedimentary depression that runs in a northeast direction with rather gentle bedding slopes towards the axial part. The size of the basin is about 625×250 km, and the maximum thickness is approximately 900 m. Sediments that fill the basin are referred to as the Polissya Series (Group) in Ukraine, the Polesie Series (Group) in Poland, and the Sherovichi and Belarus Series (Groups) in Belarus. The basin is separated from the Krestsy aulacogen by the Velizh saddle [25]. The Volyn-Orsha basin is divided into two sub-basins (Volyn and Orsha) by the Central-Belarussian (or Rogachev-Bobruisk) saddle [26].

The initial stage in the development of the Volyn-Orsha basin was characterized by slow, gradual subsidence and accumulation of fine-grained sediments, including mudstones, siltstones and fine-grained sandstones [19]. At this stage, the detrital material was transported from the basin margins towards the centre of the trough forming alluvial fans that were reworked by a fluvial system flowing along the long axis of the basin. This resulted in the facies boundaries running parallel to the basin margins. In the second stage, local horsts, transverse to the long axis, were developed, dividing the basin into a series of sub-basins. The most significant horst is the Rogachev-Bobruisk saddle, which separates the Volyn and Orsha sub-basins. Once the saddle was formed, these sub-basins started to develop independently and were likely fed from different sources. Feldspathic to arkose sandstones prevail in the Volyn sub-basin, while the Orsha sub-basin is dominated by quartz sandstones. Immature sediments of the Volyn sub-basin were likely locally derived, whereas sediments of the Orsha sub-basin were fluvially transported for longer distances. During the later stage in the basin evolution, the two sub-basins continued to be isolated from each other. In the Orsha sub-basin, terrigenous-carbonate (dolostone) sediments of the Lapichi Formation were accumulated, while deposition of terrigenous sediments continued in the Volyn sub-basin. The Lapichi Formation was deposited in a shallow-water, intracratonic basin with low salinity and no oceanic connection [27].

3. Polissya Group in Ukraine

The Polissya Group comprises a continental, silty to sandy, red-bed sedimentary succession that was unconformably deposited on Paleoproterozoic crystalline basement. The sedimentary thickness

 doi:10.20944/preprints202303.0518.v1

of the group gradually increases from the basin margins towards the basin axis, where it reaches 900 m [28]. The sequence is weakly deformed, forming gently dipping, open folds. The sediments are sandstones (96.8 %), siltstones (1.7 %), and mudstones (1.5 %) [29]. Sandstones are feldspathic to arkose, and poorly cemented. The presence of red-coloured siltstones in the lower part of each formation results in the rhythmicity of the whole sequence. The group is subdivided into three formations (known in the Ukrainian literature as suites): the Romeyki, Polytsi, and Zhobryn formations [30].

The Romeyki Formation is up to 380 m thick and rests on paleosols developed on the crystalline basement. It contains coarse-grained sandstones and conglomerates in the very base. The pebbles are fragments of the locally weathered crystalline rocks. The basal coarse-grained interval is overlain by a thick (up to 207 m) sequence of reddish-brown, arkose sandstones that contain interlayers of siltstones and mudstones. Clastic fragments of quartz and potassium feldspar are well-rounded and sorted. Heavy minerals are ilmenite, garnet, tourmaline, zircon, and apatite. The rocks are poorly cemented, and the cement is composed of clay minerals with rare carbonate admixtures.

The Polytsi Formation is 110 m thick and overlies the Romeyki Formation with disconformity. It is composed of rather monotonous, fine-grained sandstones and siltstones that form the second sedimentary succession. The basal part of the formation consists of an 18-meter-thick layer of brown micaceous mudstone, while the middle part is represented by brown, poorly cemented, oligomictic sandstones. The upper part of the formation consists of a variegated interlayering of sandstones and mudstones. The rocks of the formation are rich in feldspars, with accessory ilmenite, tourmaline, and zircon.

The Zhobryn Formation is developed in the axial part of the Volyn-Orsha basin. It is up to 360 m thick and is subdivided into three sub-formations, each representing a sedimentary sequence. The lower sub-formation is over 100 meters thick, with a 20- to 30-meter-thick layer of greenish-grey mudstone at the base, overlain by a 75-meter-thick layer of brown, poorly cemented, oligomictic sandstone. The middle sub-formation contains predominantly fine-grained sandstone interlayered with mudstone, which grades up-section into poorly cemented, porous, oligomictic, arkosic sandstone. The upper sub-formation consists of light-grey, poorly sorted, porous sandstones that contain up to 30 % K-feldspar.

The depositional age of the Polissya Group is poorly defined. The youngest basement rocks are the ca. 2030-1980 Ma intrusive and metavolcanic rocks of the Osnitsk-Mikashevychi Igneous Belt [31–33] and the ca. 1980-1900 Ma metavolcanic and metasedimentary rocks of the Central Belarusian Suture Zone [34]. The group is overlain with a hiatus by the terrigenous sediments of the Brody Formation in Ukraine, which is coeval to the Vilchitsy Group in Belarus. Based on U-Pb dates for detrital zircons, the maximum depositional ages for the Vilchitsy Group is 977 ± 6 Ma [35] and for the Brody Formation is 1204 ± 26 Ma (Francovschi et al., in review).

All these rocks are overlain by the volcano-sedimentary Volyn Group [36–38]. The age of the Volyn Group has been defined based on U-Pb ages of volcanic zircon at 573 ± 14 Ma [39]. Sill-like dolerite bodies intrude the Polissya Group. According to their chemical and isotope composition, the dolerite sills belong to the Volyn flood basalt province [40]. Their maximum age is constrained at 626 ± 17 Ma by baddeleyite $^{206}Pb/^{238}U$ dating [39].

There have been several attempts to date sediments of the Polissya Group using various methods. Early age determinations were based on K-Ar dating, which yielded ages of 815–700 Ma for mica and feldspar and 980–880 Ma for whole rocks [27,41]. A K–Ar age of 1055 Ma was also obtained [42]. More recent studies were based on U-Pb dating of detrital zircons. The Maximum Depositional Age (MDA) of the Polissya Group was defined at 1018 ± 43 Ma for sandstone of the Polytsy Formation [8] and 954 ± 12 Ma for sandstone of the Rudnya Formation, Belarus Group, which may be equivalent to the middle-upper part of the Polissya Group in Ukraine [35]. Similar results (960-950 Ma) have also been obtained for detrital zircons from sandstones sampled from the basal and upper parts of the Belarus Group in Belarus [43].

 doi:10.20944/preprints202303.0518.v1

4. Sample

A sandstone sample was collected from drill-core #70 at a depth of 106.5 m (Figures 1 and 2). It represents the uppermost part of the Romeyki Formation, the lowermost unit of the Polissya Group. The boundary with the overlying Polytsi Formation is defined at a depth of 104.3 m. The analysed sample is fine-grained, greenish-grey quartz sandstone that is bedded and poorly cemented. The bedding is defined by thin seams of claystone. Numerous zircon crystals were separated from this rock, which are predominantly 100 to 150 μm in size, colourless, and transparent. Grains are well to very well rounded and have an equant to short-prismatic shape.

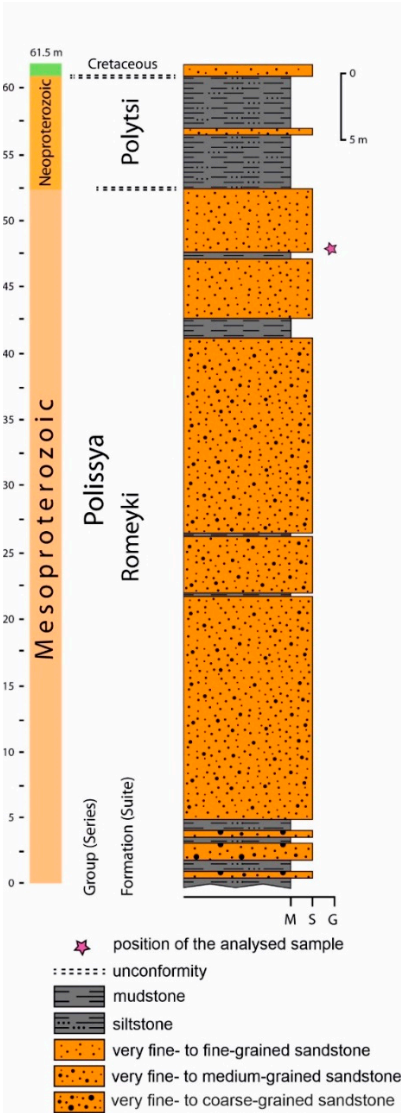

Figure 2. Lithostratigraphic column of the pre-Cretaceous section of drill-core #70, Volyn sub-basin of the Volyn-Orsha basin, showing the stratigraphic position of the analysed sandstone.

5. Methods

Zircons were separated from sandstone sample using a shaking table, magnetic separator and heavy liquids in the M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation of the National Academy of Sciences of Ukraine. About 1 kg of the analyzed sample was processed. The separated zircons were mounted in epoxy, polished and imaged using reflected and transmitted light. U–Pb zircon geochronology was performed at the University of California, Santa Barbara, using a Nu Plasma HR MC-ICP-MS and a Photon Machines Excite 193 excimer ArF laser-ablation system equipped with a HeLex sample cell. During the analysis, spots were ablated for 15 seconds at a rate of 4 Hz and an intensity of approximately 1 J/cm^2, resulting in a pit depth of about 5 μm. The analyses

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 30 March 2023 doi:10.20944/preprints202303.0518.v1

were preceded by a 15-second baseline measurement and analyses of unknowns were corrected using the 91500 reference material (1062 Ma; [44]). The reference material was analysed after approximately every 10 analyses for quality control purposes. Secondary reference materials, including GJ-1 (602 Ma; [45]), and Plešovice (337 Ma; [46]), were analysed and returned dates within 2% of the accepted $^{206}Pb/^{238}U$ ages. All errors are reported within 2 standard deviations (σ).

The kernel density estimation (KDE) plots were generated by using the Python pandas.DataFrame.plot.kde library. The selected estimator bandwidth was the 'scott' method, which was set to a value of 0.05.

6. Results

In total, 103 zircon crystals were dated. Seventeen grains were more than 10 % discordant and were excluded from further consideration. Eighty-six grains yielded concordant ages, with most of them (74 grains, or 86 %) in the age interval between 1655 ± 3 and 1044 ± 16 Ma, with two well-defined peaks at ca. 1630 and 1230 Ma. The next group (7 zircons, 8 %) yielded ages between 2004 ± 9 and 1799 ± 9 Ma. Finally, 5 zircons had even older ages, extending back to 3260.3 ± 4.3 Ma (Supplementary Table 1, Figure 3). The youngest dated grain yielded a date of 1044 ± 16 Ma, and the next three youngest grains formed a tight group with a weighted mean age of 1079 ± 8 Ma. We accept this age as the MDA of the Romeyki Formation.

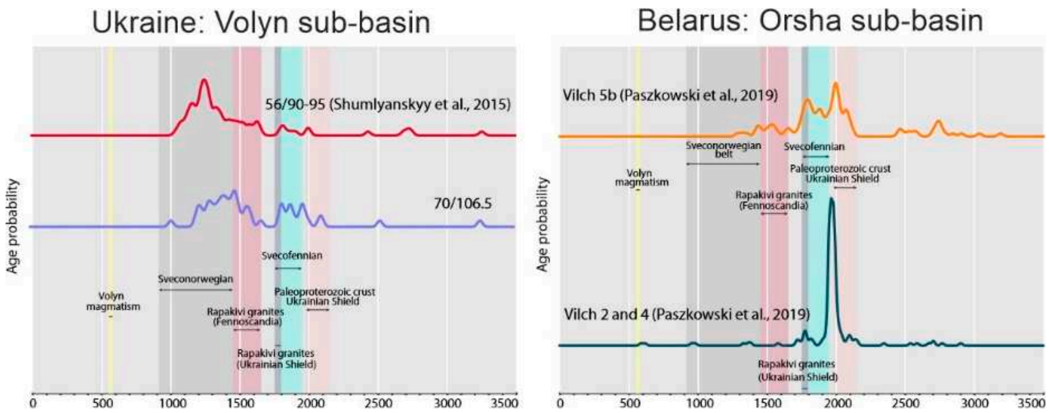

Figure 3. The detrital zircon age spectra (KDE plots) for the sediments filling the Volyn and Orsha sub-basins. Arrangement of the plots on the diagram broadly corresponds to their position in the sedimentary succession.

Zircons from all age groups show significant variations in U (ranging from 10 to 1630 ppm) and Th (ranging from 2 to 185 ppm) concentrations, which are irrespective of the age. The Th/U ratio varies from 0.17 to 1.18, indicating the predominantly igneous source of zircon.

7. Discussion

7.1. Provenance of the Volyn-Orsha basin sediments

Previous researchers reported the results of U-Pb dating of detrital zircons from different levels of the sedimentary succession filling the Volyn-Orsha basin [8,35]. The lowermost samples, Vilch-2 and Vilch-4, represent the basal Pinsk Formation of the Belarus Group and are dominated by a ca. 1.97 Ga population (Figure 3). These zircons correspond in age to the Osnitsk-Mikashevychi Igneous Belt and Central Belarusian Suture Zone [31–33,47]. A similar pattern was previously observed for the lowermost sediments filling the late Paleozoic Donets basin, as a part of the Pripyat-Dnieper-Donets aulacogen (see Figure 1), where the basal sandstones contain zircon populations predominantly derived from the immediately underlying crystalline rocks [48]. In the Belarusian samples, there are also smaller peaks at ca. 2.15-2.10 Ga and 1.85-1.70 Ga, which match the age of the local crystalline basement. Older (as old as ca. 2.90 Ga) and younger zircons are rare and are unlikely to be derived from a local source.

The sample Vilch-5b represents the Orsha Formation, which sits in the middle part of the Belarus Group [35]. The age pattern of detrital zircons in this sample is different from that in the lower samples. The main population has an age of ca. 2.00 Ga, but it does not define a single peak. Other important peaks are at ca. 2075, 1890, and 1790 Ma. All these peaks, except the one at 1890 Ma, can be explained by local sources. Sixty-eight percent of zircons in this sample fall within the age range of 2150 to 1700 Ma. There is also a significant group of zircons (15 %) with ages between 3200 and 2450 Ma, which could have been derived from the Meso- to Neoarchean complexes of the Ukrainian Shield [49–54]. The remaining zircons in this sample have ages between 1660 and 1280 Ma. Most of them could have been derived from the AMCG complexes of Fennoscandia, except for the youngest zircons, which were more distally derived (see below).

Sample 56/90-95 [8] represents the middle part of the Polissya Group in the Volyn sub-basin of Ukraine and is in a stratigraphically similar position to sample Vilch-5b of the Orsha sub-basin. However, these two samples show significant difference in their provenance. Characteristically, zircons from the Ukrainian sample cluster into two large groups with ages of 2200-1800 and 1600-1200 Ma. Similarly to sample 70/106.5, which is presented in this work, zircons from sample 56/90-95 were predominantly derived from distal sources. Only a relatively small number of zircons, dated at ca. 2110, 2010 and 1970 Ma, could have been derived from the local crystalline basement. At the same time, zircons from the ca. 2080-2020 Ma Zhytomyr and 1800-1740 Ma Korosten complexes, which are abundant in the area, are absent in sample 56/90-95. It has been shown that the Sveconorwegian belt and Finnish rapakivi intrusions and associated rocks could have been a source of some zircons of the 1500–1000 Ma population [8].

In sample 70/106.5 (this study), Paleoproterozoic, ca. 2000-1800 Ma, zircons constitute one of the main groups and, in general, correspond to the time of formation of the crystalline basement that directly underlies the Volyn-Orsha basin. However, a closer examination of the zircon ages reveals significant differences between the spectrum of detrital ages and the ages of the potential local zircon sources. For instance, 1800-1740 Ma zircons are absent in the studied sample, whereas this age interval corresponds to the time of active intraplate magmatism in the Ukrainian Shield [55–57]. Zircons with ages of 2150-2050 Ma are also absent in the studied sample, whereas rocks of this age are widely distributed in the Ukrainian Shield [58–61]. The studied sample contains a small number of ca. 2000 Ma zircons that could have been sourced from the Osnitsk-Mikashevychi igneous belt. Igneous and metamorphic complexes formed between 1950 and 1800 Ma could have been derived from the Svecofennian orogen (e.g., [62]).

Zircons with ca. 1650-1500 Ma dates could have been sourced from large anorthosite-mangerite-charnockite-granite complexes in SW Fennoscandia: Mazury (1520-1500 Ma, [64,65], Viborg (1640-1630 Ma, [66]), Riga (1580 Ma, [67]), and Salmi (1550-1530 Ma, [66,68]. Also, potential sources of the ca. 1500-1000 Ma zircons, which are the most abundant in the studied sample, are unknown in Sarmatia, but could have been derived from the Sveconorwegian belt [69]. In addition, a small population of Archean zircons were likely derived from Archean complexes widely developed in the Ukrainian Shield [49,51–54].

In summary, zircons found in the Orsha sub-basin were mainly derived from local sources. In contrast, zircons in the Volyn sub-basin were predominantly derived from distal sources. This observation agrees with previous results, which indicated different sources for the Volyn and Orsha sub-basins [19]. This also precludes transportation of the sedimentary material from NE to SW. Our data suggest that detritus was transported along the axis of the basin in the NE direction, into the continent.

In the context of long-distance transport of the sedimentary material, a fluvial transport, exceeding 3000 km was suggested for ca. 1.1 Ga zircons derived from the Grenville orogenic mountains to Neoproterozoic sedimentary basins in Laurentia [70,71]. Importantly, these basins have similar maximum depositional ages of ca. 1.1 Ga, and similar to the Polissya Group patterns of U-Pb detrital zircon dates. It was inferred that the Grenville orogenic belt must have been high enough to facilitate long-distance fluvial transport of the detrital material. This scenario might also apply to the Polissya Group sediments.

7.2. Possible link to Amazonia

Many studies have suggested a strong link between Baltica and Amazonia during the Proterozoic (e.g., [56,61,72,73]. The available information indicates that these continents possibly existed as a single entity in Nuna and Rodinia supercontinents until Rodinia breakup in the late Neoproterozoic (e.g., [37,63,74–79]. According to most reconstructions, the western margin of Baltica (the Trans-European Suture Zone) was attached to Amazonia, suggesting that the Volyn-Orsha basin possibly continued farther westward towards Amazonia. Available geological data do not indicate any closure of the Volyn-Orsha basin towards the Trans-European Suture Zone; rather, it is sharply aborted by the zone. If this reconstruction is correct, then Amazonia might have been supplying detrital material to the basin, rather than the distally-located Sveconorwegian rocks. It is worth noting that basins of broadly similar age, sediment composition, and tectonic setting are also known in Amazonia [80].

Geochronological and isotope geochemical data regarding the Amazonian complexes [81–84] suggest that these areas could have been a suitable source of detrital material deposited in the Volyn sub-basin. Indeed, active magmatism in Amazonia started at ca. 2200 Ma and lasted until ca. 1250 Ma. After 1250 Ma, it continued until ca. 950-900 Ma, but on a smaller scale (see overview in [61]).

The Meso- to Neoproterozoic orogenic belts in Amazonia extend to the NW Baltica (Figure 4). As a result, geochronological and isotope geochemical data do not allow for unequivocal differentiation between Amazonia and Baltica sources. The sedimentary fill of the Volyn sub-basin is relatively poorly-sorted, poorly-rounded, and subarkosic. This conflicts with long distance (either from Amazonia or Baltica) transport from their sources. In contrast, the Orsha sub-basin is filled with well-sorted and rounded, mainly quartz sediments derived predominantly from local sources.

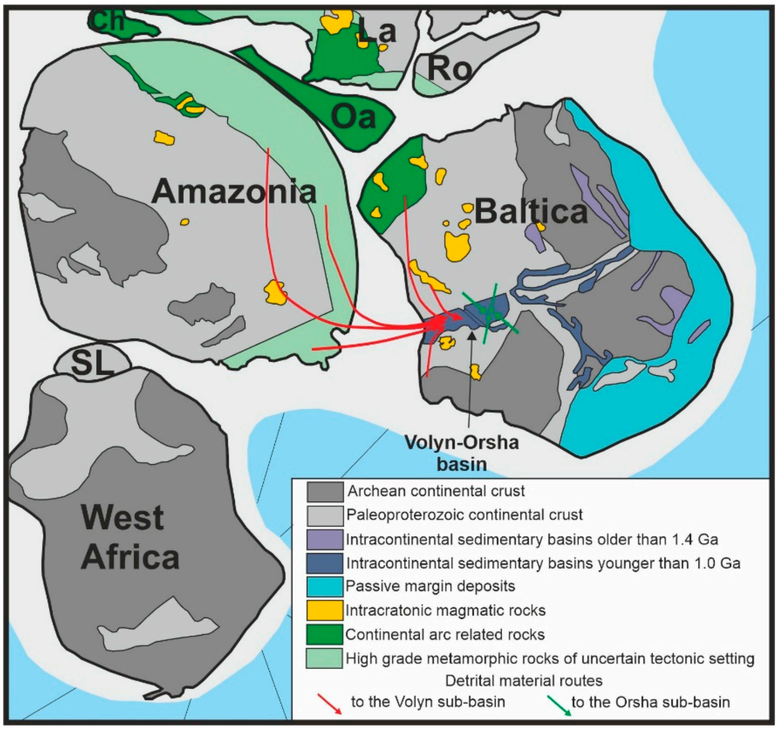

Figure 4. Position of Baltica within the Meso-Neoproterozoic supercontinent Rodinia (modified after [63]). The possible routes of detrital material for the Volyn and Orsha sub-basins are shown. SL stands for the São Luis block, La – for Laurentia continent, Ro – for the Rockall plateau, Ch – for the Chortis block, and Oa – for the Oaxaquia block.

Interestingly, the detrital zircon age distribution patterns in Neoproterozoic sedimentary samples collected from the stratigraphic units overlying the Volyn-Orsha basin [35] change drastically after the breakup of Rodinia. Samples of the Vilchitsy Group, which were deposited above

 doi:10.20944/preprints202303.0518.v1

the Belarus Group, demonstrate a wide spectrum of zircon ages with MDAs of ca. 1000 Ma, similar to those observed in the Polissya Group. In contrast, all younger Ediacaran samples reveal patterns with a strong peak at ca. 1500 Ma and a small peak at ca. 1800 Ma, and lack younger ages except for ca. 570 Ma zircons related to the Volyn flood basalt province. Such a difference in the detrital zircon patterns indicates a sharp change in the provenance. After Rodinia breakup, Amazonia sources became unavailable and disappeared from the sedimentary record of Baltica.

In Meso-Neoproterozoic continental reconstructions, some authors [63,85–87] place the Oaxaquia block of Mexico between Baltica and Amazonia (see Figure 4). However, this model contradicts the available geological and geochronological information regarding the late Mesoproterozoic to early Neoproterozoic evolution of SW Baltica. Between 1300 and 1000 Ma, the Oaxaquia block experienced intense arc magmatism and emplacement of AMCG complexes. At 1000-980 Ma it was affected by a granulite facies tectonothermal event [87]. None of these events are recorded in SW Baltica, where the latest known magmatic event was dated at ca. 1720 Ma [88]. SW Baltica lost its adjacent landmasses during the Rodinia breakup, and the latter event possibly explains disappearance of the above-mentioned, ca. 1500 Ma detrital zircon age mode from the late Ediacaran – Palaeozoic sedimentary record of SW Baltica.

7.3. Possible triggers for basin initiation

To explain the origin of the Meso- to Neoproterozoic Volyn-Orsha intracontinental sedimentary basin in Baltica, we need to consider possible reasons for extension, decrease in lithospheric rigidity, and potential link to major suture zones. Considering the linear shape of the Volyn-Middle Russia rift system, it has long been considered as an aulacogen (fossil rift; [89]). However, lack of associated magmatism and connection to the contemporaneous continental margin at either end of the system seem to challenge this view. Further, if this rift system indeed developed at ca. 1.0 Ga, as detrital zircon ages and micropaleontological data suggest, Baltica was in a compressional rather than an extensional regime. Considering compressional regime at ca. 1.0 Ga, the Volyn-Middle Russia rift system could be impactogen basin formed in front of the orogenic belt. However, evidence for the Meso- to Neoproterozoic orogeny at either end of the rift system is not strong, in fact it runs roughly parallel to the Sveconorwegian orogenic belt.

It has been suggested [11,21,72,90–92] that during the time interval ca. 1.2 to 0.9 Ga, Baltica (either together with Amazonia or alone) underwent a clockwise ~90° rotation and collided with Laurentia, resulting in the formation of the Grenvillian – Sveconorwegian – Sunsas orogenic belt. These processes likely resulted in significant shear stresses that were probably concentrated along Paleoproterozoic sutures [21]. These stresses could have caused localized extension and subsidence, but did not result in magmatic activity or significant tectonic re-arrangement. Furthermore, the rotation of the craton, with deep mantle keels of orogens generating localized stresses, along a fulcrum centred in NW Fennoscandia, would result in a greater degree of extension along the eastern margin of Baltica (in its present position) with respect to its western margin.

Another factor that can facilitate subsidence is the presence of an eclogitized subducted slab. It has been shown that eclogites can survive in the lithosphere for a long time, avoiding lower crustal delamination [93]. Such a dense and heated lithosphere would tend to subside under conditions of lithospheric extension caused by tectonic factors.

The Sarmatia (and Volga-Uralia) – Fennoscandia suture zone has a “diffuse” structure and contains a number of displaced crustal blocks that could be either exotic or derived from all three crustal segments [11,47,94]. It has been shown that Paleoproterozoic eclogites, probably representing relics of the subducted oceanic plate, occur in the suture zone [47,95–97]. Hence, the development of the system of Meso- to Neoproterozoic sedimentary basins in Baltica could have been triggered by a combination of several factors, including (1) the localized lithospheric extension along ancient suture zones caused by the differential movement (rotation) of Baltica and by continental collisions that produced the Grenvillian – Sveconorwegian – Sunsas orogenic belts, and (2) the pulling down by eclogite lithosphere in the suture zones.

8. Conclusions

At the end of the Mesoproterozoic to the beginning of the Neoproterozoic, an extended system of amagmatic sedimentary basins developed in Baltica. These basins generally follow sutures between the major crustal blocks that constitute the craton. The depositional age of the basins is poorly known, but the maximum depositional age has been herein defined as ca. 1000-950 Ma. This age broadly corresponds to the time of clockwise ~90° rotation of Baltica and the formation of the Grenvillian – Sveconorwegian – Sunsas orogenic belts, which caused lithospheric extension to be concentrated in the old suture zones. In addition, subsidence was facilitated by the presence of eclogites derived from the subducted oceanic crust.

The westernmost part of the system of sedimentary basins, known as the Volyn-Orsha basin, comprises two sub-basins (Volyn and Orsha), separated by the Rogachev-Bobruisk saddle. Despite their close spatial relationships, the two sub-basins reveal drastically different provenances. The clastic sediments infilling the Orsha sub-basin were predominantly derived from local crystalline basement rocks. In contrast, the detrital material deposited in the Volyn sub-basin was transported from distant areas, possibly from the Sveconorwegian orogen in NW Baltica, or the Sunsas orogen in Amazonia.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Table S1: Results of detrital zircon U-Pb dating.

Author Contributions: Conceptualization, L.S. and A.B.; validation, L.S., A.B. and S.W.; formal analysis, L.S. and I.F.; investigation, L.S., I.T. and V.M..; resources, I.T. and V.M..; writing—original draft preparation, L.S.; writing—review and editing, A.B., I.F., and S.W.; visualization, I.F.; supervision, S.W.; funding acquisition, A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research is part of project No. 2021/43/P/ST10/02283 co-funded by the National Science Centre and the European Union Framework Programme for Research and Innovation Horizon 2020 under the Marie Skłodowska-Curie grant agreement No. 945339. Participation by IF was supported by Project PN-III-P1-1.1-PD-2021-0400, No. 60/2022 of the Romanian Executive Agency for Higher Education, Research, Development and Innovation, UEFISCDI. Participation by AB was supported by the ACS PRF grant 624840ND2.

Data Availability Statement: All the analytical data are presented in the paper, including the supplementary materials.

Acknowledgments: We dedicate this contribution to heroic efforts of the Armed Forces of Ukraine and the resilience and courage of the Ukrainian people. LS acknowledges the Curtin Research Office for providing support. Andrew Kylander-Clark at UCSB helped to generate the LA-ICP-MS detrital zircon U-Pb data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cawood, P.A.; Nemchin, A.A. Source regions for Laurentian margin sediments: Constraints from U/Pb dating of detrital zircon in the Newfoundland Appalachians. *Geol. Soc. Am. Bull.* **2001**, 113, 1234–1246. https://doi.org/10.1130/0016-7606(2001)113<1234:PDOTEL>2.0.CO;2
2. Fedo, C.M.; Sircombe, K.N.; Rainbird, R.H. Detrital Zircon Analysis of the Sedimentary Record. *Rev. Mineral. Geochem.* **2003**, 53, 277-303. https://doi.org/10.2113/0530277
3. Cawood, P.A.; Hawkesworth, C.J.; Dhuime, B. Detrital zircon record and tectonic setting. *Geology* **2012**, 40, 875–878. https://doi.org/10.1130/G32945.1
4. Barham, M.; Kirkland, C.L.; Handoko, A.D. Understanding ancient tectonic settings through detrital zircon analysis. *Earth Planet. Sci. Let.* **2022**, 583, 117425. https://doi.org/10.1016/j.epsl.2022.117425
5. Condie, K.C.; Belousova, E.; Griffin, W.L.; Sircombe, K.N., 2009, Granitoid events in space and time: Constraints from igneous and detrital zircon age spectra. *Gondwana Res.* **2009**, 15, 228–242, https://doi.org/10.1016/j.gr.2008.06.001
6. Hawkesworth, C.; Dhuime, B.; Pietranik, A.; Cawood, P.; Kemp, T.; Storey, C. The generation and evolution of the continental crust. *J. Geol. Soc.* **2010**, 167, 229–248, https://doi.org/10.1144/0016-76492009-072

7. Voice, P.J.; Kowalewski, M.; Eriksson, K.A. Quantifying the timing and rate of crustal evolution: global compilation of radiometrically dated detrital zircon grains. *J. Geol.* **2011**, 119, 109–126. https://doi.org/10.1086/658295
8. Shumlyanskyy, L.; Hawkesworth, C.; Dhuime, B.; Billström, K.; Claesson, S.; Storey, C. $^{207}Pb/^{206}Pb$ ages and Hf isotope composition of zircons from sedimentary rocks of the Ukrainian shield: crustal growth of the south-western part of East European craton from Archaean to Neoproterozoic. *Precam. Res.* **2015**, 260, 39–54. https://doi.org/10.1016/j.precamres.2015.01.007
9. Andersen, T.; Kristoffersen, M.; Elburg, M.A. How far can we trust provenance and crustal evolution information from detrital zircons? A South African case study. *Gondwana Res.* **2016**, 34, 129-148. https://doi.org/10.1016/j.gr.2016.03.003
10. Joshi, K.B.; Banerji, U.S., Dubey, C.P.; Oliveira, E.P. Detrital zircons in crustal evolution: a perspective from the Indian subcontinent. *Lithosphere* **2022**, 3099822. https://doi.org/10.2113/2022/3099822
11. Bogdanova, S.V.; Bingen, B.; Gorbatschev, R.; Kheraskova, T.N.; Kozlov, V.I.; Puchkov, V.N.; Volozh, Y.A. The East European Craton (Baltica) before and during the assembly of Rodinia. *Precam. Res.* **2008**, 160, 23–45. https://doi.org/10.1016/j.precamres.2007.04.024
12. McLelland, J.M.; Selleck, B.W. Late- to post-tectonic setting of some major Proterozoic anorthosite – mangerite – charnockite – granite (AMCG) suites. *Can. Mineral.* **2010**, 48, 729-750. https://doi.org/10.3749/canmin.48.4.729
13. Gorbatschev, R. The Transscandinavian Igneous Belt - introduction and background". In Högdahl, K.; Andersson, U.B. and Eklund, O. (eds.). The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geol. Survey Finland, Spec. Paper* **2004**, 37, 9–15.
14. Andersson, U.B.; Sjöström, H.; Högdahl, K.; Eklund, O. The Transscandinavian Igneous Belt, evolutionary models. In Högdahl, K.; Andersson, U.B. and Eklund, O. (eds.). The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geol. Survey Finland, Spec. Paper* **2004**, 37, 104–112.
15. Slagstad, T.; Roberts, N.M.W.; Markens, R.; Røhr, T.; Schiellerup, H. A non-collisional, accretionary Sveconorwegian orogen. *Terra Nova* **2013**, 25, 30–37. https://doi.org/10.1111/ter.12001
16. Bingen, B.; Viola, G.; Möller, C.; Vander Auwera, J.; Laurent, L.; Yi, K. The Sveconorwegian orogeny. *Gondwana Res.* **2021**, 90, 273-313. https://doi.org/10.1016/j.gr.2020.10.014
17. Nikishin, A.M.; Ziegler, P.A.; Stephenson, R.A.; Cloetingh, S.A.P.L.; Furne, A.V.; Fokin, P.A.; Ershov, A.V.; Bolotov, S.N.; Korotaev, M.V.; Alekseev, A.S.; Gorbachev, V.I.; Shipilov, E.V.; Lankreijer, A.; Bembinova, E.Y.; Shalimov, I.V. Late Precambrian to Triassic history of the East European Craton: dynamics of sedimentary basin evolution. *Tectonophys.* **1996**, 268, 23-63. https://doi.org/10.1016/S0040-1951(96)00228-4
18. Kheraskova, T.N.; Volozh, Y.A.; Vorontsov, A.K.; Pevzner, L.A.; Sychkin, N.I. 2002. Sedimentation conditions at the Central East European platform in the Riphean and Early Vendian. *Lithol. Miner. Resour.* **2002**, 37 (1), 68–81. https://doi.org/10.1023/A:1013639623107
19. Nagornyi, M.A. (1990) *Tectonics of the Volyn-Middle Russian system of basins*. Minsk, Nauka i tekhnika publisher, **1990**, 105 p. (in Russian).
20. Bogdanova, S.V.; Pashkevich, I.K.; Gorbatschev, R.; Orlyuk, M.I. Riphean rifting and major Palaeoproterozoic crustal boundaries in the basement of the East European Craton: geology and geophysics. *Tectonophys.* **1996**, 268, 1-21. https://doi.org/10.1016/S0040-1951(96)00232-6
21. Baluev, A.S. Geodynamics of the Riphean stage in the evolution of the northern passive margin of the East European Craton. *Geotectonics* **2006**, 40 (3), 183–196.
22. Velikanov, V.A.; Aseeva, E.A.; Fedonkin, M.A. *The Vendian of Ukraine*. Kyiv, Naukova Dumka publisher, **1983**, 164 p. (In Russian).
23. Keller, B.M. *The upper Proterozoic of the Russian Platform (Riphean and Vendian). Essays on the regional geology of the USSR*. Moscow, Moscow University publisher, **1968**, 101 p. (In Russian).
24. Kheraskova, T.N. The significance of N.S. Shatsky's works on the tectonics of ancient platforms and their petroleum resources from a modern viewpoint. *Geotectonics* **2005**, 39 (4), 253–271.
25. Aisberg, R.E.; Garetskiy, R.G.; Karabanov A.K. Peculiarities of formation of rift and passive-margin basins in the west of the East-European platform. *Litasfera* **2009**, 1(30), 3-10. (In Russian)
26. Kruchek, S.A.; Matveyev, A.V.; Yakubovskaya, T.V.; Obukhovskaya, T.G.; Naidenkov, I.V.; Aksamentova, N.V.; Arkhipova, A.A.; Pap, A.M.; Veretennikov, N.V.; Makhnach, A.S.; Laptsevich, A.G.; Shkuratov, V.I.; Piskun, L.V.; Zinovenko, G.V.; Abramenko, V.I.; Pushkin, V.I.; Nekrjata, N.S.; Plax, D.P.; Obukhovskaya, V.Y.; Sachenko, N.F.; Antipenko, S.V.; Golubtsov, V.K.; Tolstosheyev, V.I.; Klimenko, Z.M.; Monkevich,

K.N.; Karimova, L.A.; Akimets, V.S.; Burlak, A.F.; Davydik, K.I.; Murashko, L.I.; Azhgirevich, L.F.; Anoshko, Y.I.; Rylova, T.B.; Khursevich, G.K.; Sanko, A.F.; Velichkevich, F.Y.; Karabanov, A.K.; Motuzko, A.N.; Ilkevich, G.I.; Makhnach, N.A.; Mikhailov, N.D.; Zernitskaya, V.P.; Yakovleva, N.S. *Stratigraphic Charts of Precambrian and Phanerozoic deposits of Belarus: Explanatory note*. Minsk. State Enterprise «BelNIGRI» **2010**, 282 p. (In Russian).

27. Makhnach, A.S.; Veretennikov, N.V.; Shkuratov, V.I.; Bordon, V.E. *Riphean and Vendian of Belarus*. Nauka i tekhnika publisher, **1976**, 360 p. (in Russian).
28. Ryabenko, V.A.; Mikhnytska, T.P. *The Riphean of Ukraine*. Kyiv, Ukrainian State geological Institute, **2000**, 180 p. (In Ukrainian).
29. Hozhyk, P.F.; Semenenko, V.M.; Maslun, N.V.; Poletaev, V.I.; Ivanik, M.M.; Mikhnytska, T.P.; Velikanov, V.Y.; Melnychuk, V.G.; Konstantynenko, L.I.; Kyryanov, V.V.; Tsehelniuk, P.D.; Kotlyar, O.U.; Berchenko, O.I.; Vdovenko, M.V.; Shulha, V.F.; Nemyrovska, T.I.; Shchoholev, O.K.; Boyarina, N.I.; Efimenko, V.I.; Pyatkova, D.M.; Plotnikova, L.F.; Leshchukh, R.Y.; Zhabina, N.M.; Shevchuk, O.A.; Yakushyn, L.M.; Anikeeva, O.V.; Veklych, O.D.; Prykhodko, M.G.; Tuziak, Y.M.; Matlai, L.M.; Dorotiak, Y.B.; Shainoha, I.V.; Klymenko, Y.V.; Hotsaniuk, G.I. *Stratigraphy of the upper Proterozoic, Palaeozoic and Mesozoic of Ukraine*. Kyiv, **2013**, Lohos, 637 p. (In Ukrainian).
30. Vlasov, B.I.; Volovnik, B.Y.; Gruzman, G.G. Peculiarities of the structure and the principle of the stratification of the Polissya Group in Volyn. *Geol. J.* **1972**, 32 (4), 56–67. (in Russian).
31. Claesson, S.; Bogdanova, S.V.; Bibikova, E.V.; Gorbatschev, R. Isotopic evidence for Palaeorpoterozoic accretion in the basement of the East European Craton. *Tectonophys.* **2001**, 339, 1–18. https://doi.org/10.1016/S0040-1951(01)00031-2
32. Shumlyanskyy, L. Geochemistry of the Osnitsk-Mikashevichy volcanoplutonic complex of the Ukrainian Shield. *Geochem. Int.* **2014**, 52, 912–924. https://doi.org/10.1134/S0016702914110081
33. Vysotskyi, O.B.; Stepanyuk, L.M.; Shumlyanskyy, L.V. The U-Pb and Lu-Hf zircon geochronology (LA-ICP-MS) of felsic volcanic rocks of the Klesiv Group (Volyn Domain of the Ukrainian Shield). In: *Abstract vol. "The Precambrian: rock associations and their ore potential"*, Kyiv, Ukraine, 22 September **2020**, p. 20-22. (In Ukrainian).
34. Bogdanova, S.V.; Bibikova, E.V.; Gorbatchev, R. Palaeoproterozoic U-Pb zircon ages from Belorussia: New tectonic implications for the East European Craton. *Precam. Res.* **1994**, 68, 231–240. https://doi.org/10.1016/0301-9268(94)90031-0
35. Paszkowski, M.; Budzyn, B.; Mazur, S.; Slama, J.; Shumlyanskyy, L.; Środoń, J.; Dhuime, B.; Kedzior, A.; Liivamagi, S.; Pisarzowska, A. Detrital zircon U–Pb and Hf constraints on provenance and timing of deposition of the Mesoproterozoic to Cambrian sedimentary cover of the East European Craton, Belarus. *Precam. Res.* **2019**, 331, 1–19. https://doi.org/10.1016/j.precamres.2019.105352
36. Kuzmenkova, O.F.; Nosova, A.A.; Shumlyanskyy, L.V. A comparison of the Neoproterozoic Volyn-Brest magmatic province with large continental flood basalt provinces of the world, the nature of low-Ti and high-Ti basic magmatism. *Litasfera* **2010**, 33, 3–16. (In Russian)
37. Shumlyanskyy, L.V.; Andréasson, P.G.; Buchan, K.L.; Ernst, R.E. The Volynian Flood Basalt Province and coeval (Ediacaran) magmatism in Baltoscandia and Laurentia. *Mineral. J. (Ukr.)* **2007**, 29, 47–55.
38. Shumlyanskyy, L.V. The evolution of the Vendian continental flood basalt magmatism of the Volyn region. *Mineral. J. (Ukr.)* **2012**, 34(4), 50-68. (In Ukrainian).
39. Shumlyanskyy, L.; Nosova, A.; Billström, K.; Söderlund, U.; Andréasson, P.-G.; Kuzmenkova, O. The U-Pb zircon and baddeleyite ages of the Neoproterozoic Volyn Large Igneous Province: Implication for the age of the magmatism and the nature of a crustal contaminant. *GFF* **2016**, 138, 17–30. https://doi.org/10.1080/11035897.2015.1123289
40. Shumlyanskyy, L.V.; Kuzmenkova, O.F.; Tsymbal, S.M.; Melnychuk, V.G.; Tarasko I.V. Geochemistry and isotope composition of Sr and Nd in intrusive bodies of the high-Ti dolerites of the Volyn region. *Mineral. J. (Ukr.)* **2011**, 33(2), 72-82. (In Ukrainian).
41. Chebanenko, I.I.; Vyshnyakov, I.B.; Vlasov, B.I. *Geotectonics of the Volyno-Podolian region*. Naukova Dumka publisher **1990**, 244 p. (in Russian).
42. Nechaev, S.V. Geochronology of the Late Precambrian deposits of the south-western slope of the Russian platform. In: *Abstract vol. of the Conference on the Late Precambrian (Riphean) of the Russian Platform*. Nauka Publisher, 1974, pp. 40–47. (in Russian).

43. Zaitseva, T.S.; Kuzmenkova, O.F.; Kuznetsov, A.B.; Laptsevich, A.G.; Adamskaya, E.V. U-Th-Pb LA-ICP-MS dating of detrital zircons from the Riphean deposits of the Volyn-Orsha paleobasin (drill hole Kormyanskaya, Belarus). In: *Stratigraphy of the upper Precambrian.* Abstract vol. of the VII Russian conference (Saint-Petersburg, 21-24 September **2021**), p. 71-74. (In Russian).
44. Wiedenbeck, M.; Alle, P.; Corfu, F.; Griffin, W.L.; Meier, M.; Oberli, F.; von Quadt, A.; Roddick, J.C.; Spiegel, W. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace-element and REE analyses. *Geostand. Newslett.* **1995**, 19, 1–23. https://doi.org/10.1111/j.1751-908X.1995.tb00147.x
45. Jackson, S.E.; Pearson, N.J.; Griffin, W.L.; Belousova E.A. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chem. Geol.* **2004**, 211, 47–69. https://doi.org/10.1016/j.chemgeo.2004.06.017
46. Sláma, J.; Košler, J.; Condon, D.J.; Crowley, J.L.; Gerdes, A.; Hanchar, J.M.; Horstwood, M.S.; Morris, G.A.; Nasdala, L.; Norberg, N. Plešovice zircon – a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chem. Geol.* **2008**, 249, 1–35. https://doi.org/10.1016/j.chemgeo.2007.11.005
47. Shumlyanskyy, L.; Tsymbal, S.; Kusiak, M.; Wilde, S.A.; Nemchin, A.A.; Tarasko, I.; Shumlianska, L.; Hofmann, M. U-Pb age and Hf isotope systematics of zircon from eclogite xenoliths in Devonian kimberlites: Preliminary data on the Archaean roots in the junction zone between the Sarmatian and Fennoscandian segments of the East European Platform. *Geosciences* **2021**, 11, 487. https://doi.org/10.3390/geosciences11120487
48. Shumlyanskyy, L.V.; Hofmann, M.; Borodynya, B.V.; Artemenko, G.V. The local sources of detrital material in Middle Devonian quartzites of the Donets basin: results of U-Pb LA-ICP-MS zircon dating. *Mineral. J. (Ukr.)* 2021, 43(3), 85-88. https://doi.org/10.15407/mineraljournal.43.03.085
49. Shcherbak, N.P.; Artemenko, G.V.; Lesnaya, I.M.; Ponomarenko, O.M. *Geochronology of the Early Precambrian. The Archean.* Naukova Dumka publisher 2005, 243 p. (in Russian).
50. Ponomarenko, A.N.; Lesnaya, I.M.; Ziultsle, O.V.; Hatsenko, V.A.; Dovbush, T.I.; Kanunikova, L.I.; Shumlyanskyy, L.V. Neoarchean of the Ros-Tikych Domain of the Ukrainian Shield. *Geochem. Ore Form.* **2010**, 28, 11-16. (In Russian).
51. Claesson, S.; Bibikova, E.; Shumlyanskyy, L.; Dhuime, B.; Hawkesworth, C. The oldest crust in the Ukrainian Shield – Eoarchean U-Pb ages and Hf-Nd constraints from enderbites and metasediments. In *Continent formation through time*; Van Kranendonk, N.M.W., Parman, S., Shirey, S., Clift, P.D., Eds.; Geol. Soc. London: London, UK **2015**, 389, 227–259. https://doi.org/10.1144/SP389.9
52. Claesson, S.; Bibikova, E.V.; Shumlyanskyy, L.; Whitehouse, M.J.; Billström, K. Can oxygen isotopes in magmatic zircon be modified by metamorphism? A case study from the Eoarchean Dniester-Bug Series, Ukrainian Shield. *Precam. Res.* **2016**, 273, 1–11. https://doi.org/10.1016/j.precamres.2015.11.002
53. Shumlyanskyy, L.; Wilde, S.A.; Nemchin, A.A.; Claesson, S.; Billström, K.; Bagiński, B. Eoarchean rock association in the Dniester-Bouh Domain of the Ukrainian shield: a suite of LILE-depleted enderbites and mafic granulites. *Precam. Res.* **2021**, 352, 106001. https://doi.org/10.1016/j.precamres.2020.106001
54. Shumlyanskyy, L.V. Geochemistry of pyroxene plagioclase gneisses (enderbites) of the Bouh area and Hf isotope composition in zircons. *Mineral. J. (Ukr.)* 2012, 34 (2), 64–79 (In Ukrainian).
55. Shumlyanskyy, L.; Hawkesworth, C.; Billström, K.; Bogdanova, S.; Mytrokhyn, O.; Romer, R.; Dhuime, B.; Claesson, S.; Ernst, R.; Whitehouse, M.; Bilan O. The origin of the Palaeoproterozoic AMCG complexes in the Ukrainian Shield: New U-Pb ages and Hf isotopes in zircon. *Precam. Res.* **2017**, 292, 216–239. https://doi.org/10.1016/j.precamres.2017.02.009
56. Shumlyanskyy, L.; Ernst, R.E.; Albekov, A.; Söderlund, U.; Wilde, S.A.; Bekker, A. The early Statherian (ca. 1800-1750 Ma) Prutivka-Novogol large igneous province of Sarmatia: geochronology and implication for the Nuna/Columbia supercontinent reconstruction. *Precam. Res.* **2021**, 358, 106185. https://doi.org/10.1016/j.precamres.2021.106185
57. Shumlyanskyy, L.; Franz, G.; Glynn, S.; Mytrokhyn, O.; Voznyak, D.; Bilan, O. Geochronology of granites of the western Korosten AMCG complex (Ukrainian Shield): implications for the emplacement history and origin of miarolitic pegmatites. *European J. Mineral.* **2021**, 33, 703-716. https://doi.org/10.5194/ejm-33-703-2021
58. Ponomarenko, A.N.; Stepanyuk, L.M.; Shumlyanskyy, L.V. Geochronology and geodynamics of the Paleoproterozoic of the Ukrainian Shield. *Mineral. J. (Ukr.)* **2014**, 36(2), 48-60. (In Ukrainian).
59. Shumlyanskyy, L.V.; Stepanyuk, L.M.; Claesson, S.; Rudenko, K.V.; Bekker, A.Y. The U-Pb zircon and monazite geochronology of granitoids of the Zhytomyr and Sheremetiv complexes, the Northwestern

region of the Ukrainian Shield. *Mineral. J. (Ukr.)* **2018**, 40, 63–85. (In Ukrainian) https://doi.org/10.15407/mineraljournal.40.02.063
60. Liebmann, J.; Spencer, C.J.; Kirkland, C.L.; Bucholz, C.E.; Xia, X.P.; Martin, L.; Kitchen, N.; Shumlyanskyy, L. Coupling sulfur and oxygen isotope ratios in sediment melts across the Archean-Proterozoic transition. *Geochim. Cosmochim. Acta* **2021**, 307, 242-257. https://doi.org/10.1016/j.gca.2021.05.045
61. Johansson, Å.; Bingen, B.; Huhma, H.; Waight, T.; Vestergaard, R.; Soesoo, A.; Skridlaite, G.; Krzeminska, E.; Shumlyanskyy, L.; Holland, M.E.; Holm-Denoma, C.; Teixeira, W.; Faleiros, F.; Ribeiro, B.; Jacobs, J.; Wang, C.C.; Thomas, R.; Macey, P.; Kirkland, C.; Hartnady, M.; Eglington, B.; Puetz, S.; Condie, K.C. A geochronological review of magmatism along the external margin of Columbia and in the Grenville-age orogens forming the core of Rodinia. *Precam. Res.* **2022**, 371, 106463. https://doi.org/10.1016/j.precamres.2021.106463
62. Bogdanova, S.V.; Gorbatschev, R.; Garetsky, R.G. EUROPE|East European Craton. *Reference Module in EarthSystems and Environmental Sciences*, Elsevier, **2016**. https://doi.org/10.1016/B978-0-12-409548-9.10020-X.
63. Li, Z.X.; Bogdanova, S.V.; Collins, A.S.; Davidson, A.; De Waele, B.; Ernst, R.E.; Fitzsimons, I.C.W.; Fuck, R.A.; Gladkochub, D.P.; Jacobs, J.; Karlstrom, K.E.; Lu, S.; Natapov, L.M.; Pease, V.; Pisarevsky, S.A.; Thrane, K.; Vernikovsky, V. Assembly, configuration, and break-up history of Rodinia: A synthesis. *Precam. Res.* **2008**, 160, 179–210. https://doi.org/10.1016/j.precamres.2007.04.021
64. Wiszniewska, J.; Kusiak, M.A.; Krzemińska, E.; Dörr, W.; Suzuki, K. Mesoproterozoic AMCG granitoids in the Mazury complex, NE Poland – a geochronological update. In: *Granitoids in Poland*, AM Monograph No. 1., **2007**, 31–39.
65. Wiszniewska, J.; Krzemińska, E. Advances in geochronology in the Suwałki anorthosite massif and subsequent granite veins, northeastern Poland. *Precam. Res.* **2021**, 361, 106265. https://doi.org/10.1016/j.precamres.2021.106265
66. Neymark, L.A.; Amelin, J.V.; Lapin, A.M. 1994. Pb–Nd–Sr isotopic and chemical constraints on the origin of the 1.54–1.56 Ma, Salmi rapakivi-anorthosite batholith (Karelia, Russia). *Mineral. Petrol.* **1994**, 50, 173–193. https://doi.org/10.1007/BF01160146
67. Rämö, O.T.; Huhma, H.; Kirs, J. Radiogenic isotopes of the Estonian and Latvian rapakivi granite suites: new data from the concealed Precambrian of the East European craton. *Precam. Res.* **1996**, 79, 209–226. https://doi.org/10.1016/S0301-9268(95)00083-6
68. Amelin, Y.V.; Larin, A.M.; Tucker, R.D. Chronology of multiphase emplacement of the Salmi rapakivi–anorthosite complex, Baltic Shield: implications for magmatic evolution. *Contrib. Mineral. Petrol.* **1996**, 127, 353–368. https://doi.org/10.1007/s004100050285
69. Bingen, B.; Solli, A. Geochronology of magmatism in the Caledonian and Sveconorwegian belts of Baltica: synopsis for detrital zircon provenance studies. *Norwegian J. Geol.* **2009**, 89, 267–290.
70. Rainbird, R.H.; McNicoll, V.J.; Thériault, R.J.; Heaman, L.M.; Abbott, J.G.; Long, D.G.F.; Thorkelson, D.J. Pan-continental river system draining Grenville orogen recorded by U-Pb and Sm-Nd geochronology of Neoproterozoic quartzarenites and mudrocks, Northwestern Canada. *J. Geol.* **1997**, *105*(1), 1–17. https://doi.org/10.2307/30079882
71. Rainbird, R.H.; Heaman, L.M.; Young, G. Sampling Laurentia: Detrital zircon geochronology offers evidence for an extensive Neoproterozoic river system originating from the Grenville orogen. *Geology* **1992**, 20, 351-354. https://doi.org/10.1130/0091-7613(1992)020<0351:SLDZGO>2.3.CO;2
72. Johansson, Å. Baltica, Amazonia and the SAMBA connection – 1000 million years of neighbourhood during the Proterozoic? *Precam. Res.* **2009**, 175, 221–234. https://doi.org/10.1016/j.precamres.2009.09.011
73. Terentiev, R.A.; Santosh, M. Baltica (East European Craton) and Atlantica (Amazonian and West African Cratons) in the Proterozoic: The pre-Columbia connection. *Earth-Sci. Rev.* 2020, 210, 1–27. https://doi.org/10.1016/j. earscirev.2020.103378
74. Aleinikoff, J.N.; Zartman, R.E.; Walter, M.; Rankin, D.W.; Lyttle, P.T.; Burton, W.C. U-Pb ages of metarhyolites of the Catoctin and Mount Rogers Formations, central and southern Appalachians: evidence for two pulses of Iapetan rifting. *Am. J. Sci.* **1995**, 255, 428-454. https://doi.org/10.2475/ajs.295.4.428
75. Bingen, B.; Demaiffe, D; van Breemen, O. The 616 Ma old Egersund dike swarm, SW Norway, and Late Neoproterozoic opening of the Iapetus Ocean. *J. Geol.* **1998**, 106, 565-574. https://doi.org/10.1086/516042
76. Weil, A.B.; Van der Voo, R.; Mac Niocaill, C.; Meert J.G. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma. *Earth Planet. Sci. Let.* **1998**, 154, 13–24. https://doi.org/10.1016/S0012-821X(97)00127-1

77. Hartz, E.H.; Torsvik, T.H. Baltica upside down: a new plate tectonic model for Rodinia and the Iapetus Ocean. *Geology* **2002**, 30, 255-258. https://doi.org/10.1130/0091-7613(2002)030<0255:BUDANP>2.0.CO;2
78. Meert, J.G.; Torsvik T.H. The making and unmaking of a supercontinent: Rodinia revisited. *Tectonophys.* **2003**, 375, 261– 288. doi:10.1016/S0040-1951(03)00342-1
79. Torsvik, T.H. The Rodinia jigsaw puzzle. *Science* **2003**, 300, 1379-1381. https://doi.org/10.1126/science.1083469
80. de Brito Neves, B.B.; Reinhardt A. Fuck, R.A.; da Cruz Campanha, G.A. The Statherian taphrogenesis of the South American Platform. *Braz. J. Geol.* **2022**, 52(1), e2021053. https://doi.org/10.1590/2317-4889202220210053
81. Augustsson, C.; Willner, A.P.; Rüsing, T.; Niemeyer, H.; Gerdes, A.; Adams, C.J.; Miller, H. The crustal evolution of South America from a zircon Hf-isotope perspective. *Terra Nova* **2016**, 28: 128–137. https://doi.org/10.1111/ter.12200
82. Roverato, M.; Giordano, D.; Giovanardi, T.; Juliani, C.; Polo, L. The 2.0–1.88 Ga Paleoproterozoic evolution of the southern Amazonian Craton (Brazil): An interpretation inferred by lithofaciological, geochemical and geochronological data. *Gondwana Res.* **2019**, 70, 1–24. https://doi.org/10.1016/j.gr.2018.12.005
83. Ribeiro, B.V.; Lopes, L.B.L.; Kirkland, C.L.; Cawood, P.A.; Faleiros, F.M.; Hartnady, M.I.H.; Teixeira, W.; Mulder, J.A.; Roberts, N.M.W.; Tassinari, C.C.G. Growing the Paleo- to Mesoproterozoic margin of the SW Amazonia and the transition from an accretionary to a collisional system. *Precam. Res.* **2022**, 381, 106841. https://doi.org/10.1016/j.precamres.2022.106841
84. Almeida, M.E.; Nascimento, R.S.C.; Mendes, T.A.; Santos, J.O.S.; Macambira, M.J.B.; Vasconcelos, P.; Pinheiro, S.S. An outline of Paleoproterozoic-Mesoproterozoic crustal evolution of the NW Amazon craton and implications for the Columbia Supercontinent. *Int. Geol. Rev.* **2022**, 64, 3195-3229. https://doi.org/10.1080/00206814.2021.2025158
85. Valencia-Morales, Y.T.; Weber, B.; Tazzo-Rangel, M.D.; González-Guzmán, R.; Frei, D.; Quintana-Delgado, J.A.; Rivera-Moreno, E.N. Early Mesoproterozoic inliers in the Chiapas Massif Complex of southern Mexico: implications on Oaxaquia-Amazonia-Baltica configuration. *Precam. Res.* **2022**, 373, 106611. https://doi.org/10.1016/j.precamres.2022.106611
86. Keppie, J.D. Terranes of Mexico revisited: a 1.3 billion year odyssey. *Int. Geol. Rev.* **2004**, 46, 765–794. https://doi.org/10.2747/0020-6814.46.9.765
87. Keppie, J.D.; Ortega-Gutiérrez, F. 1.3–0.9 Ga Oaxaquia (Mexico): Remnant of an arc/backarc on the northern margin of Amazonia. *J. South Am. Earth Sci.* **2010**, 29, 21–27. https://doi.org/10.1016/j.jsames.2009.07.001
88. Elming, S.-Å.; Shumlyanskyy, L.; Kravchenko, S.; Layer, P.; Söderlund, U. Proterozoic basic dykes in the Ukrainian Shield: a palaeomagnetic, geochronologic and geochemical study – the accretion of the Ukrainian Shield to Fennoscandia. *Precam. Res.* **2010**, 178, 119–135. https://doi.org/10.1016/j.precamres.2010.02.001
89. Gordasnikov, Y.Y.; Troitskiy Y.Y. The Middle Russian aulacogen is a core structure of the Moscow sineclise. *Soviet geology* 1966, 12, 50–58. (In Russian)
90. Cawood, P.A.; Strachan, R.A.; Pisarevsky, S.A.; Gladkochub, D.P.; Murphy, J.B. Linking collisional and accretionary orogens during Rodinia assembly and breakup: implications for models of supercontinent cycles. *Earth Planet. Sci. Let.* **2016**, 449, 118–126. https://doi.org/10.1016/j.epsl.2016.05.049
91. Evans, D.A.D.; Mitchell, R.N. Assembly and breakup of the core of Paleoproterozoic –Mesoproterozoic supercontinent Nuna. *Geology* **2011**, 39, 443–446. https://doi.org/10.1130/G31654.1
92. Salminen, J., Elming, S.-Å., Layer, P. Timing the break-up of the Baltica and Laurentia connection in Nuna – Rapid plate motion oscillation and plate tectonics in the Mesoproterozoic. *Precam. Res.* **2023**, 384, 106923. https://doi.org/10.1016/j.precamres.2022.106923
93. Buntin, S.; Artemieva, I.M.; Malehmir, A.; Thybo, H.; Malinowski, M.; Högdahl, K.; Janik, T.; Buske S. Long-lived Paleoproterozoic eclogitic lower crust. *Nature Comm.* **2021**, 12, 6553. https://doi.org/10.1038/s41467-021-26878-5
94. Mężyk, M.; Malinowski, M.; Mazur, S. Structure of a diffuse suture between Fennoscandia and Sarmatia in SE Poland based on interpretation of regional reflection seismic profiles supported by unsupervised clustering. *Precam. Res.* **2021**, 358, 106176. https://doi.org/10.1016/j.precamres.2021.106176
95. Tsymbal, S.N. Kimberlites of the central part of the Prypyat swell, Ukraine. *Mineral. J. (Ukr.)* **2003**, 25, 70–87. (In Russian)

96. Garetsky, R.G.; Karatayev, G.I. A tectonogeodynamic model for the junction zone between the Fennoscandian and Sarmatian segments of the East European Platform. *Russ. Geol. Geophys.* **2011**, 52, 1228–1235. https://doi.org/10.1016/j.rgg.2011.09.013
97. Kvasnytsya, V.; Shumlyanskyy, L. Native gold and diamonds from the Palaeoproterozoic terrigenous rocks of the Bilokorovychi basin, North-Western part of the Ukrainian shield. *Mineral. J. (Ukr.)* **2018**, 40 (3), 23-38. https://doi.org/10.15407/mineraljournal.40.03.023