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What is the age of the Udzha paleorift?: U-Pb age of detrital zircons from Udzha basin terrigenous succession, northern Siberia*

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The Udzha paleorift is located between the Anabar and Olenek rivers and is a key structure indicative of the breakup of the Nuna supercontinent. However, the age of initiation and duration of paleorift activity is not defined nowadays. Here we present new U-Pb data for detrital zircons from two terrigenous and volcanic-sedimentary successions of the Udzha sedimentary basin (Unguokhtakh and Udzha Formation), from terrigenous rocks overlying the Udzha basin (Tomtor Formation), and from the sandstone of the lower Mesoproterozoic Mukun Group in the northwest part of Anabar region. The dating results show that sedimentation in the Udzha rift basin began later than ca 1459 Ma, and the duration of the rift activity is estimated as not longer than 73 My. The Udzha rift basin was an isolated basin in the northern part of Siberia, and detrital material came from local sources. A previously unknown source for tuff-sandstone of Unguokhtah Formation with an age of 1850 Ma has been identified, which corresponds by age to the Paleoproterozoic post-orogenic magmatism of the Siberian Craton. In the Neoproterozoic, detrital material of the Tomtor Formation was supplied from the northeast, and the sources were igneous suites of active margin or collision settings.

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The maximum depositional age of Tomtor Formation is estimated as 565 Ma on the youngest zircon population, which suggests an over 800 Ma gap in sedimentation in northern Siberia in Meso-Neoproterozoic.

Keywords: Udzha paleorift, Siberia, Mesoproterozoic, Neoproterozoic, provenances, U-Pb dating, detrital zircons, Nuna, Rodinia.

1. Introduction

The Udzha paleorift is located in the northern part of the Siberian Craton between the Olenek Uplift and the Anabar Shield and is a N-S-trending structure, which is traced from the northern margin deep into the Craton (Fig. 1). The structure of the Udzha paleorift is established mainly from geophysical and drilling data (Okhlopkov et al., 1987; Prokopiev et al., 2001) and is considered to be a blind branch of a triple junction rift system. The rift nature of the Udzha structure is also confirmed by the wide distribution of igneous rocks in the sedimentary sequence, represented by both volcanic lavas and intrusions, which are overlain by the late Neoproterozoic (Vendian) sedimentary rocks (Fig. 2B and 2C). However, the age of initiation and time of duration of the Udzha paleorift remains uncertain. The earliest age estimates for the rift initiation were based on K-Ar dating of volcanic lava flows, intrusions and sedimentary glauconite and ranged from 1320 to 820 Ma (Erlich and Stepanenko, 1965; Semikhatov and Serebryakov, 1983). Thus, for a long time it was believed that the Udzha rift basin evolved over more than 500 Ma, reflecting the late Neoproterozoic breakup of the Rodinia supercontinent (Prokopiev et al., 2001) rather than the breakup of the Mesoproterozoic Nuna (Columbia) supercontinent. More recent dating of dykes yielded Ar-Ar plagioclase age at 1074 ± 11 Ma (Gladkochub et al., 2009) and U-Pb apatite age at 1386 ± 30 Ma (Malyshev et al., 2018) pointing to the Mezoproterozoic age of the host strata. Today the lower age limit is estimated at ~1500 Ma based on the results of paleomagnetic studies of volcanic rocks at the base of the volcanic-sedimentary succession of the paleorift (Pasenko and Malyshev, 2020).

In this paper, we present new data on U-Pb dating of detrital zircons from terrigenous and volcanic-sedimentary rocks of the Udzha rift basin, which allow us to get a new constraint on the maximum depositional age and present a provenance study.

2. Geological structure and history of the Udzha paleorift and adjacent parts of the Anabar Shield

The Precambrian part of the succession of Udzha paleorift is represented by six formations (in ascending stratigraphic order, Fig. 2C): Ulakhan-Kurung, Unguokhtakh, Khapchanyr, Udzha, Tomtor, and Turkut (Shpunt et al., 1976). The total thickness of this part of the succession, according to drilling data, is estimated at more than 1900 m, while the lower contact of the Ulakhan-Kurung Formation with the basement was not exposed. Below we briefly describe the sedimentary sequence and the the depositional environments of these units, following studies by B. R. Shpunt with co-authors (Shpunt et al., 1976; 1982).

The knowledge about the crystalline basement of the Udzha structure is very scanty. All available information is based on the few xenoliths found in the Mesoproterozoic (Lower and Middle Riphean) volcanic rocks and Mesozoic-Cenozoic pebbles. The studied fragments are represented by various sedimentary rocks metamorphosed in epidote-am-

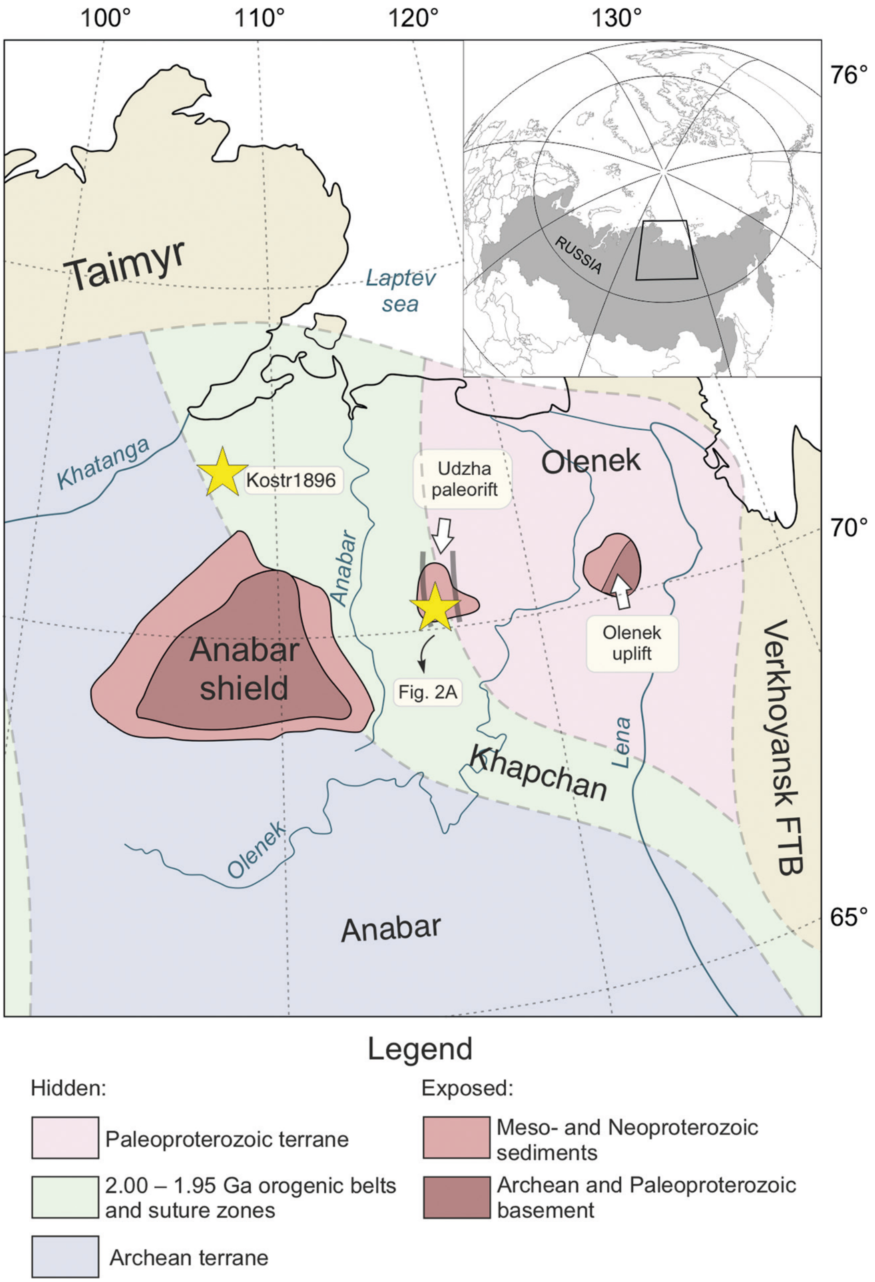

Fig. 1. Generalized map of the northern part of the Siberian Platform, outcrops of the crystalline basement and Meso-Neoproterozoic sedimentary cover after (Khudoley et al., 2015), basement structure after (Donskaya, 2020), simplified

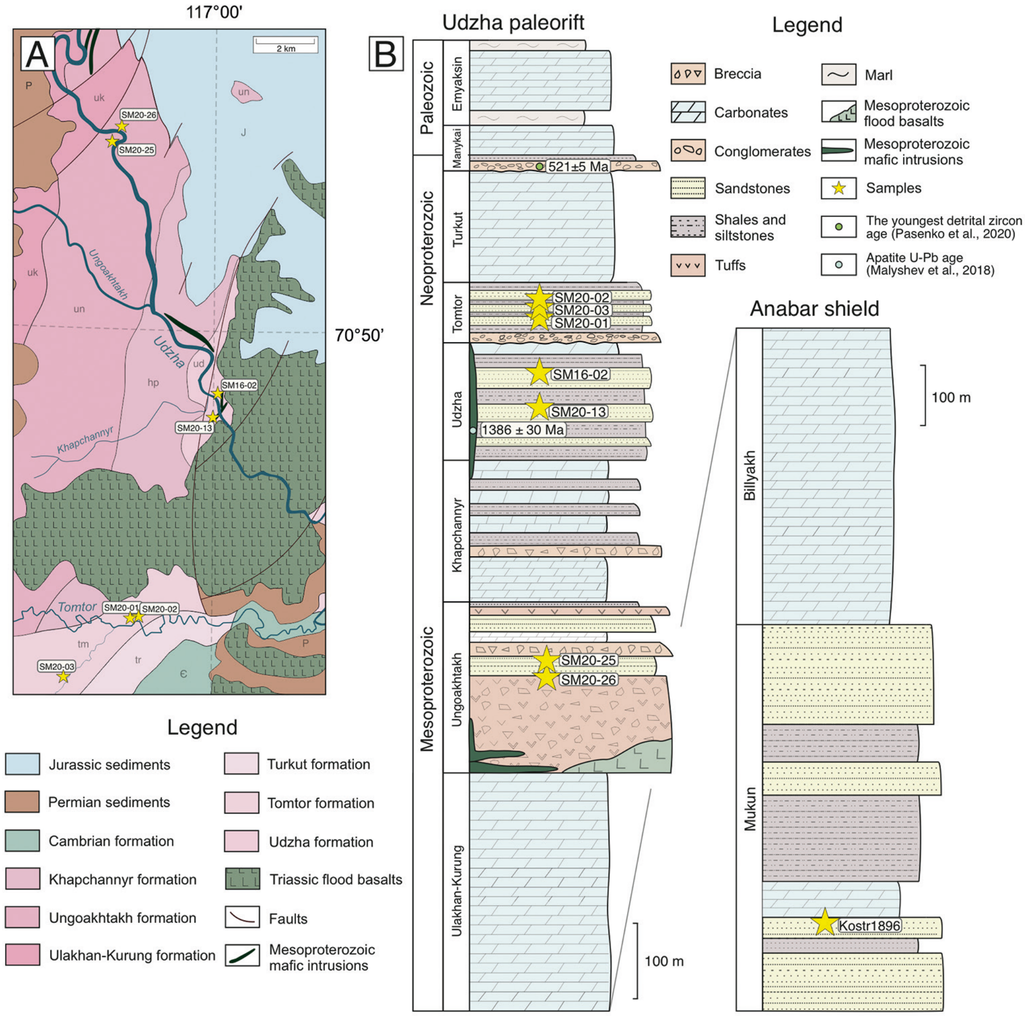

Fig. 2. (A) Map of the middle reaches of the Udzha River with location of sampling points, after (Erlikh and Stepanenko, 1965, simplified and modified). (B) Generalized stratigraphy of the Udzha section (Okhlopkov et al., 1987) and the Mesoproterozoic section of the Kostrominskaya well (Panteleev et al., 1985)

phibolite and greenschist facies. B. R. Shpunt with co-authors (Shpunt et al., 1976) noted that the metamorphic rocks exposed inthe Anabar Shield and Olenek Uplift are significantly different from the metamorphic rocks of the Udzha paleorift, which may indicate a significant difference in the composition of the basement.

The lower part of the Udzha paleorift succession is composed of rocks of the Ulakhan-Kurung Formation, more than 800 m thick. Information about its composition was obtained from boreholes, which did not penetrate the base of the unit. The lower part of the Ulakhan-Kurung Formation is represented by siltstones, mudstones, quartz sandstones, and dolomites (some researchers distinguish this part of the formation as separate unit– the Tomtor-Chymar sequence (Okhlopkov et al., 1987). The upper part of the formationis represented mainly by carbonate rocks, including stromatolitic limestones. A distinctive feature of the carbonate rocks is wide distribution of black cherts nodules, which sometimes comprises large (5 × 0.3 m) lenses extended along the bedding surfaces. Such silicified carbonates often form local small (within 10–20 m) outcrops along the banks of the middle reaches of the Udzha River.

The Unguokhtakh Formation conformably overlies carbonates of the Ulakhan-Kurung Formation and contains variety of rocks: there are mafic volcanic flows and intrusive bodies, eruptive and conglomerate breccias, tuff breccias with lenses of tuffs and tuff sandstones (Fig. 3A), siltstones and stromatolitic carbonate rocks. The total thickness of the formation is estimated at 400–450 m. Unlike the underlying Ulakhan-Kurung Formation, the Unguokhtakh Formation is well exposed. From the bottom up, along the Unguokhtakh Formation succession, there is a transition from mafic amygdalolithic volcanic rocks to volcanic-sedimentary and then to sedimentary formations. B. R. Shpunt's studies (Shpunt et al., 1976) showed that the accumulation of volcanic-sedimentary and sedimentary rocks occurred, most likely, in shallow water environments, near the islands on which volcanos were located (Fig. 3A). The accumulation of sedimentary rocks of the Unguokhtakh Formation occurred under conditions of active hypergenesis of volcanic rocks and subsequent redeposition of its products without a noticeable input of "exotic" material. The age of the rocks of the Unguokhtakh Formation was previously determined as 1150, 1320 Ma (K-Ar method) (Semikhatov and Serebryakov, 1983). Based on previous paleomagnetic studies (Pasenko and Malyshev, 2020) magmatic rocks were correlated with Kuonamka Large Igneous Province (LIP) of ~1500 Ma (U-Pb ages of intrusive bodies vary within 1483–1503 Ma (Ernst et al., 2016). On the other hand, a detailed study of the initial Pb isotope composition in the basalt lava and sills of the Unguokhtakh magmatic event shows that their initial Pb isotope composition fits the age of ~1400 Ma (Savatenkov et al., 2019).

The Khapchanyr Formation (~350 m thick) conformably overlies rocks of the Unguokhtakh Formation and is represented by massive stromatolitic dolomites in the lower part and interbedded fine-grained terrigenous and carbonate rocks in the upper part of the section. Both parts of the formation are exposed in coastal outcrops of the Udzha River near the mouth of the Unguokhtah River. According to the results of studies by B. R. Shpunt et al. (1976), deposition occurred in the shallow water environments, which is confirmed by numerous differently oriented asymmetric ripples and mudcracks (Fig. 3B). Sources of the terrigenous material of the Khapchanyr Formation were likely the weathering products of local volcanic-sedimentary complexes.

Rocks at the bottom of the Udzha Formation are represented by a unit of stromatolitic limestones. which conformably overlies the Khapchannyr Formation rocks. Most of the formation (~300 m thick) is represented by mudstones, siltstones, sandstones, and conglomerates with intercalations of carbonate rocks (Fig. 3C). According to a complex of petrographic, X-ray diffraction and geochemical studies (Shpunt et al., 1976), rocks of the Udzha Formation were accumulated in a shallow water to tidal environments. The composition of the terrigenous components of the Udzha Formation, as well as measurements of cross-bedding carried out by B. R. Shpunt in sandstones, indicated that the source of terrigenous material was likely located to the south from the Udzha paleorift and contained felsic volcanics and granitoids. Such rocks are not typical for the study region, which indicates the possible presence of a buried basement inlier to the south of the mod-

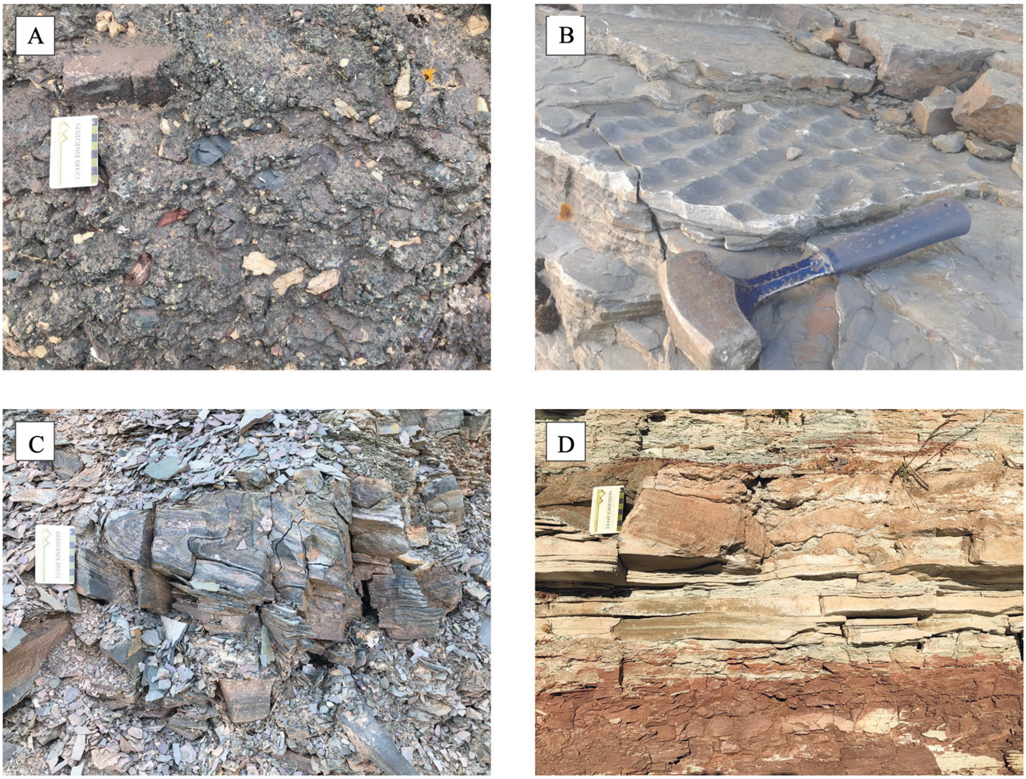

Fig. 3. Photographs of outcrops (A) of the volcaniclastic breccia of the Unguokhtakh Formation. Sampling point SM20-25; (B) ripple marks in argillaceous carbonates of the Khapchanyr Formation; (C) soft-sediment deformations in the Udzha Formation, sampling site SM20-13; (D) sandstones of the Tomtor Formation, sampling site SM20-01

ern basin of the Udzha River. Apparently, the stage of formation of the Udzha Formation was a separate period in the geological evolution of the region, different from the previous and subsequent stages of its evolution. The age of the Udzha Formation is constrained by the age of the underlying Unguakhtakh Formation (~1500 Ma), and by the age of the Great Udzha Dyke (1386 ± 30 Ma, apatite U-Pb (Malyshev et al., 2018)), which cross-cuts the sedimentary succession. Given these constraints, as well as the paleomagnetic data obtained earlier, the age of the Udzha Formation is estimated at ~1400 Ma (Pasenko and Malyshev, 2020).

The Udzha Formation is overlain by the Tomtor Formation with an unconformity marking a break in sedimentation of more than 800 Ma (Malyshev et al., 2018), and is represented by pebble conglomerates, sandstones, and siltstones (Fig. 3D). The Tomtor Formation and its correlatives are distributed throughout the north of the Siberian Platform indicating the end of the evolution of the Udzha paleorift basin as a local structure in the Neoproterozoic. Numerous measurements of cross-bedding in the terrigenous rocks of the Tomtor Formation indicate south-southwest and west-southwest paleocurrents direction. The sources of detrital material were felsic volcanic and intrusive rocks, as well as metamorphic rocks of the crystalline basement. A thick weathering crust was first formed within the basement inlier, and then the minerals resistant to hypergene processes accumulated in it and were redeposited in the channels of temporary streams flowing from the hypothetical inlier in a southerly direction. The Tomtor Formation correlates with the late Neoproterozoic (Vendian) Maastakh Formation of the Olenek Uplift, which age is estimated at 610–590 Ma (Okhlopkov et al., 1987; Vishnevskaya et al., 2017).

The Turkut Formation conformably overlies the Tomtor Formation and is also estimated to be a late Neoproterozoic (Vendian) age. It consists mainly of dolomites deposited in the tidal zone environments. The deposition of this unit marks a new stage of transgression throughout the northern part of the Siberian Platform (Shpunt et al., 1976).

Mesoproterozoic and Neoproterozoic rocks are widely distributed on the east margin of the Anabar Shield and were also penetrated by a few wells to the north of it. Three major sedimentary units are identified (in ascending stratigraphic order): Mukun Group, Billyakh Group, Staraya Rechka Formation (Gusev et al., 2016; Khudoley et al., 2015; Kuptsova et al., 2015).

The Mukun Group unconformably overlies the crystalline basement of the Anabar-Sheild. Total thickness of the Mukun Group on the east margin of the Anabar Shield varies from 16 m to 240 m, basically increasing in the north direction, and reaches 280 m in the Kostrominskaya well. Red-to light-gray-colored quartz and subarkozic arenites predominate, although shale and conglomerate interbeds occur as well. Cross-bedding, ripple marks and mud cracks are widely distributed showing that deposition occurred in fluvial to near-shore environments.

The Billyakh Group overlies the Mukun Group conformably or with local erosion. Total thickness of the Mukun Group on the east margin of the Anabar Shield is 160–200 m, and reaches 215 m in the Kostrominskaya well. Varicolored stromatolitic, often brecciated, dolomites predominate with subordinate quartz sandstone and shale units. Rocks of the Billyakh Group are separated by an unconformity into lower and upper parts, but their composition is very similar. Deposition occurred in shallow-water environments.

The Mesoproterozoic age of the Mukun and Billyakh groups is well constrained. The lowermost unit of the Mukun Group contains detrital zircons as young as 1681 ± 28 Ma, whereas the upper unit of the Billyakh Group is cut by the Chieress dyke with 1384 ± 2 Ma U-Pb baddeleyite age. On the west margin of the Anabar Shield the Byllyakh Group carbonate units are cut by mafic sill with 1502 ± 2 Ma U-Pb baddeleyite age (Ernst et al., 2016; Khudoley et al., 2015, and reference therein).

The overlying lower to middle Neoproterozoic rock units have been documented only locally. Approximately 120 m thick unit of reddish cross-bedded quartz to arkosic sandstones similar to those of the Mukun Group was documented at the southeastern margin of the Anabar Shield. However, it contains detrital zircons as young as ca 1030 Ma, showing that they are much younger that the Mukun and Byllyakh groups (Kuptsova et al., 2015). This unit has been identified in only boreholes and does not have formal name.

The Staraya Rechka Formation unconformably overlies Neoproterozoic and Mesoproterozoic sedimentary units and crystalline rocks of the Anabar Shield basement. The lowermost unit ~8–10 m thick consists of quartz to arkosic arenites with conglomerate interbeds. Overlying rocks are 100–120 m uniform dolomites with stromatolitic build-ups typical for deposition in shallow water environments. The Staraya Rechka Formation is overlain by the lower Cambrian rocks and its sandstone unit contains detrital zircon grains as young as 560 ± 6 Ma and 543 ± 23 Ma constraining its age as the latest Neoproterozoic (Vendian) (Kuptsova et al., 2015; Priyatkina et al., 2017).

3. Sampling

The studied samples were collected in the upper Udzha River for U-Pb dating. The collection is represented by 2 samples of the Unguokhtakh Formation, 2 samples of the Udzha Formation, and 3 samples of the Tomtor Formation. A sample of 5 to 8 kg in volume was taken from each outcrop for subsequent separation of a zircon monofraction. A smaller quartz sandstone sample ~2 kg of the Mukun Group was collected from the core of the Kostrominskaya well (from a depth of 1896 m). The location of the sampling outcrops and their stratigraphic settings are shown in Fig. 1. The petrographic description of the studied Udzha paleorift rock types is given below.

Unguokhtakh Formation. Sample SM 20–26, tuffite (Fig. 4A, B). The clasts (70 % of total thin section area) display irregular oval-like shape and have a size of 0.3–1 mm in common. The clasts are predominantly composed of volcanic glass, euhedral plagioclase grains, chlorite patches. Some clasts are partially to fully replaced by a fine-grained carbonate (calcite/dolomite), with crystal size < 0.05 mm, or relatively big crystals (0.1–0.2 mm).The rock matrix consists of carbonate and constitutes nearly 30 % of the total thin section area.

Udzha Formation. Sample SM 16–02, quartz arenite (Fig. 4C, D). The rock consists of detrital framework (85 %) and carbonate cement (15 %). Grains are represented by monocrystalline (~60 %) and polycrystalline quartz (~40 %). The grains show variable roundness with angular, subangular and rounded shapes. Accessory glauconite (or chlorite?) is present.

Tomtor Formation. Sample SM 20–03, quartz arenite (Fig. 4E, F). The total thin section area consists of the framework (~70 %) and cement (~30 %). The framework consists of quartz grains (95 %) of 0.5–0.7 mm in size, which are characterized by subrounded to rounded shape. Quartz grains are both monocrystalline (~50 %) and polycrystalline (~50 %). The rest of the framework consists of opaque minerals (5 %). Cement is represented by fine-grained carbonate (calcite/dolomite) with crystals of 0.02–0.05 mm in size.

4. Analytical procedure

Production and description of thin sections was carried out in the Research Park of St Petersburg State University “Center of X-ray diffraction studies”. For U-Pb dating, zircons were concentrated at three laboratories (IGGD RAS and VSEGEI (St Petersburg), GIN RAS (Moscow) according to the standard method using magnetic separation, and further separation in heavy liquids. From the resulting heavy minerals fraction, zircon grains were selected manually and mounted in epoxy resin. Samples SM16-02 and KOSTR1896 were analyzed by laser ablation ICP-MS (LA-ICP-MS) at the University of Edmonton on a Thermo Scientific ICAP-Q quadrupole mass spectrometer with a New Wave UP-2 laser attachment, following the procedure described in (Pasenko et al., 2020). Sample SM20-25 was analyzed at the Central Research Institute of VSEGEI on a secondary ion mass spectrometer SHRIMP II according to the method (Williams, 1997). Samples SM20-01, SM20-02, SM20-03, SM20-13, SM20-26 were analyzed at the Center for Collective Use “Geodynamics and Geochronology” of the Institute of Earth’s Crust, Siberian Branch, Russian Academy of Sciences (Irkutsk) using an Agilent 7900 mass spectrometer and an Analyte Excite laser ablation system. The laser spot diameter was 35 μm, the laser

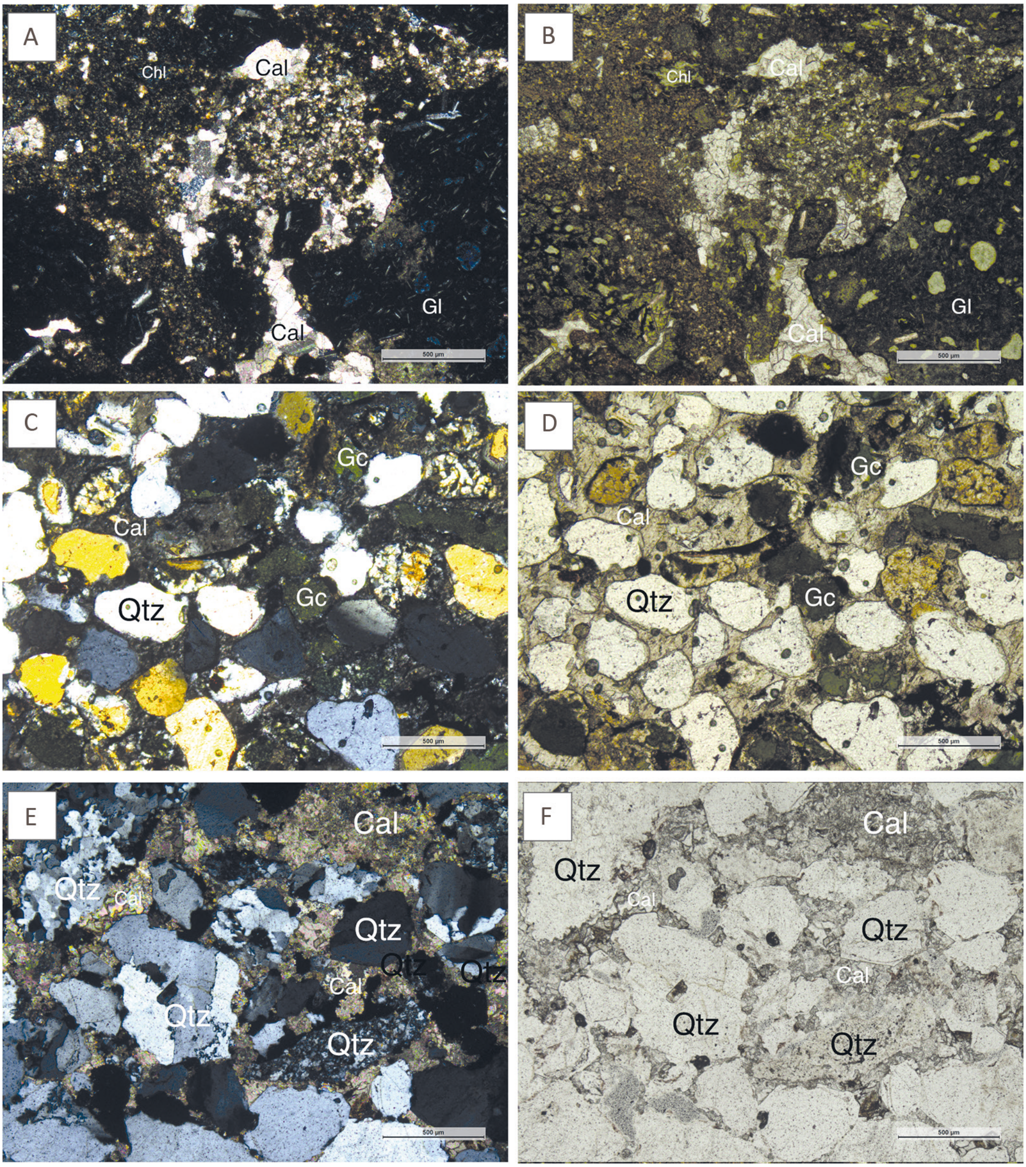

Fig. 4. Microphotographs of thin sections in transmitted light (magnification ×5): left column with an analyzer, right column without an analyzer. (A) and (B) sample SM20-26 (tuffite), (C) and (D) sample SM16-02 (quartz arenite) and (E) and (F sample SM20-03 (quartz arenite)

frequency was 5 Hz. The age was calculated relative to the Plešovice zircon standard with an age of 337.13 ± 0.37 Ma (Sláma et al., 2008). Harvard 91500 and R33 zircon standards were systematically used for quality control of measurements and for calibration during the session. For each standard zircon, concordant age estimates were obtained, consistent with the results of dating by the ID-TIMS method.

Isotope ratios were calculated using the Iolite 4.0 program (Paton et al., 2011), plotting concordia diagram, filtering and statistical data processing were performed using the

DeZirteer program (Powerman et al., 2021). Individual grain ages with discordance more that 5 % were filtered from the following interpretation. 'Best age' was calculated from the lesser error: $^{206}Pb/^{238}U$ or $^{207}Pb/^{206}Pb$ with the least % error for each analysis.

5. Results

We performed U-Pb dating of detrital zircons from 8 samples from different stratigraphic levels of the north part of Siberian Platform: sample KOSTR1896 from the Mukun Group, samples SM20-25 and SM20-26 from tuff sandstones of the Unguokhtakh Formation, samples SM16-02 and SM20-13 from sandstones of the Udzha Formation and three samples SM20-01,02,03 from sandstones of the Tomtor Formation (Fig. 2C). Since the age spectrum for samples from each unitis quite similar, we combine together description of samples from each formation/group. The dating results are shown in Fig. 5–8 and in Supplementary 1[1].

Mukun Group. 117 zircon grains were collected and dated from a sandstone sample (KOSTR1896) of the Mukun Group, 109 of which passed the discordance filter (Fig. 5). Individual ages of concordant grains are distributed in the range from 1666 to 2710 Ma. The sample is almost unimodal with a peak at 1953 Ma and two small signals at 1666 and 2699 Ma.

Unguokhtakh Formation. From two samples (SM20-25, SM20-26) of the Unguokhtakh Formation, 63 and 73 zircon grains were collected and dated respectively, and 47 and 48 grains from each sample passed the discordance filter (Fig. 6). Individual ages of concordant grains are distributed in the range from 1453 to 3065 Ma. Two large clusters with values of 1850–1950 Ma and 2500–2800 Ma are distinguished in the PDP diagram in both samples. In the first cluster, there are significant peaks with values of 1870 and 1950 Ma, while in the second cluster there are peaks at ~2500 and ~2700 Ma. There are single grains with ages ranging from 2900 to 3065 Ma. Among the youngest ages, there is a small peak at ~1500 Ma in both samples, while in sample SM20-26 on the PDP diagram, the youngest peak has a value of 1459 Ma, and the youngest grain is 1453 Ma.

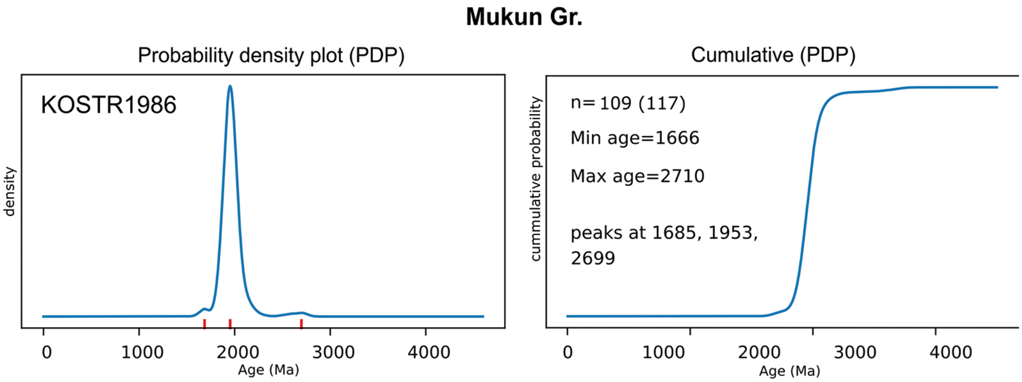

Fig. 5. Probability density plot (left) and cumulative probability plot (right) for sample KOSTR1896. Peak ages in Ma

[1] Supplementary 1 can be found at the following link: URL: https://escjournal.spbu.ru/article/view/13518/9912

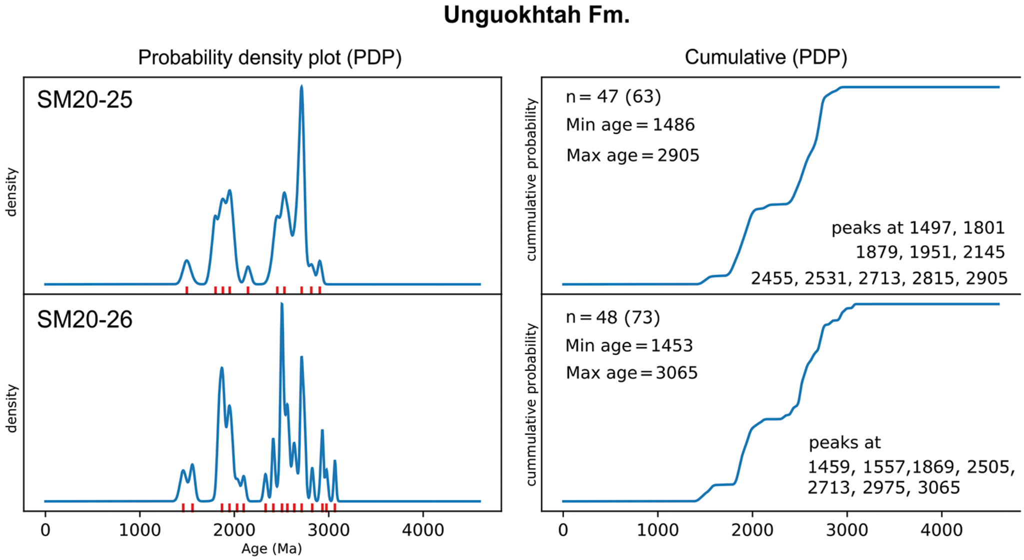

Fig. 6. Probability density plot (left) and cumulative probability plot (right) for Unguokhtakh Formation samples. Peak ages in Ma

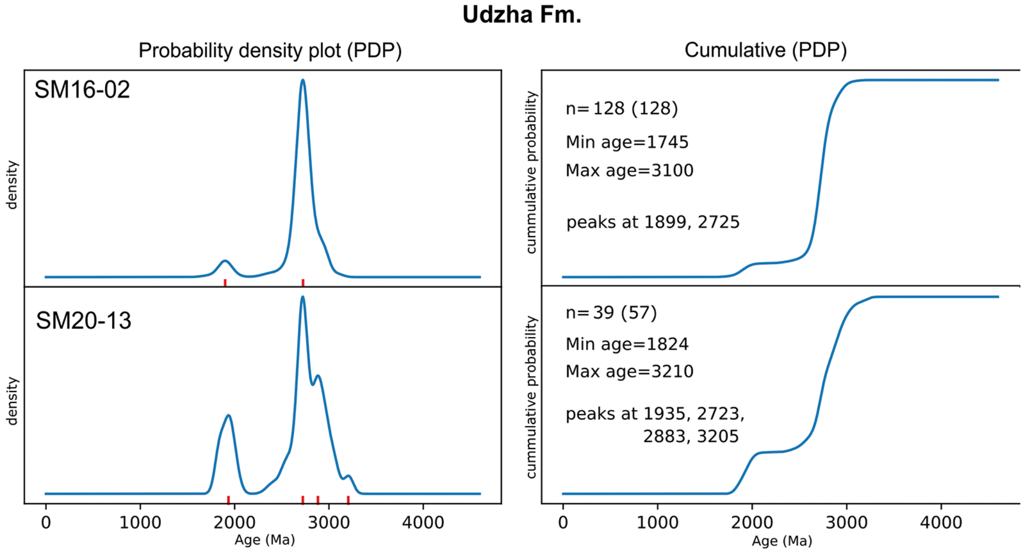

Fig. 7. Probability density plot (left) and cumulative probability plot (right) for samples from the Ulzhin Formation

Udzha Formation. From two samples (SM16-02, SM20-13) of the formation, 128 and 57 zircon grains were collected and dated respectively, andthe discordance filter was passed by 128 and 39 grains from each sample. Individual ages of concordant grains are distributed in the range from 1745 to 3210 Ma. In the PDP diagram (Fig. 7), the detrital zircon age distributions of both samples are characterized by two peaks at ~1900 and 2735 Ma. In sample SM20-13, the ancient peak is complicated by two maxima, but due to the relatively small

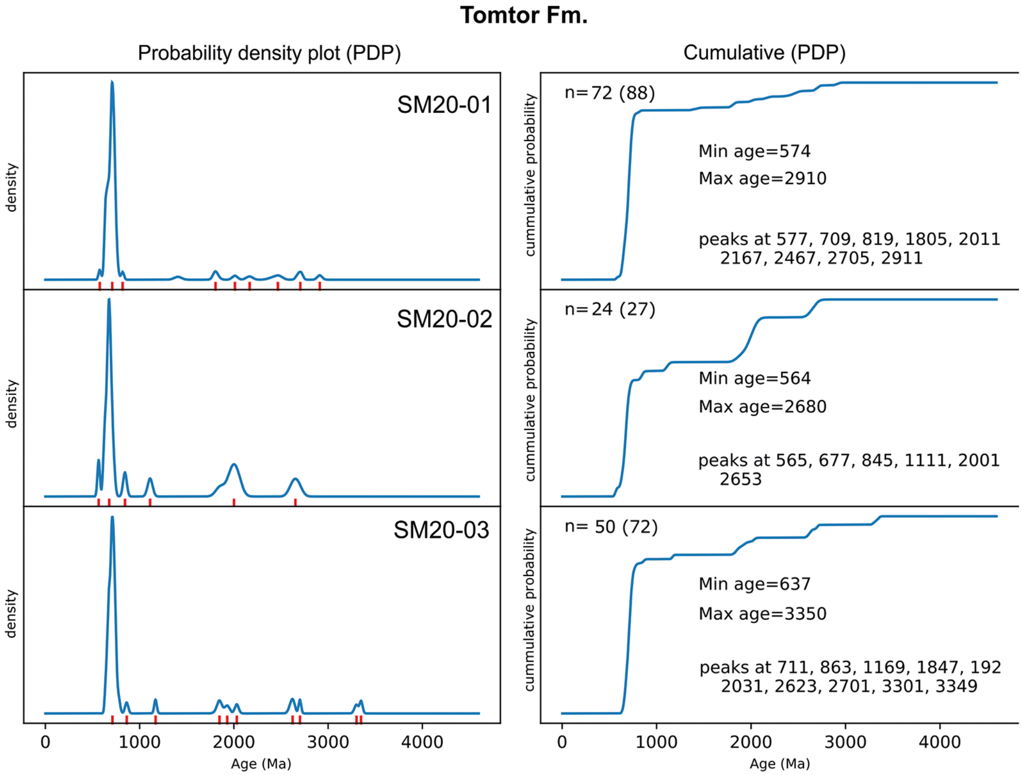

Fig. 8. Probability density plot (left) and cumulative probability plot (right) for samples of the Tomtor Formation

number of analyzed grains in this sample, we donot consider these variations due to statistical insignificance. Also, in both samples, the peak with a value of ~2700 Ma is dominant, while in sample SM16-02, which is more representative, this peak includes 90 % of all grains.

Tomtor Formation. 88, 27, and 72 zircon grains were collected from three samples (SM20-01,02,03), and dated respectively, and 72, 24, and 50 grains from each sample passed the discordance filter. Individual ages of concordant grains are distributed in the range from 564 to 3350 Ma. In the PDP diagram (Fig. 8), in all three samples, a peak with a value of ~680–710 Ma clearly dominates, which makes up to 95 % of the grains populations. The remaining peaks are well correlated between samples and are represented by ~850, 1150, 1850, 2000, 2500, and 2700 Ma. The oldest values obtained from single grains from sample SM20-03 are 3300, and 3350 Ma. The youngest peak at 565 Ma, identified in the sample SM20-02, constrains the maximum depositional age of the Tomtor Formation.

6. Discussion

6.1. Age of initiation of the Udzha paleorift

Paleogeographic reconstructions at ca. 1400 Ma suggest that the Laurentia, Baltica, and Siberia composed the Nuna supercontinent core (Evans and Mitchell, 2011; Meert and Santosh, 2017; Zhang et al., 2012). Nuna's lifespan and its break-up is a discussed sub-

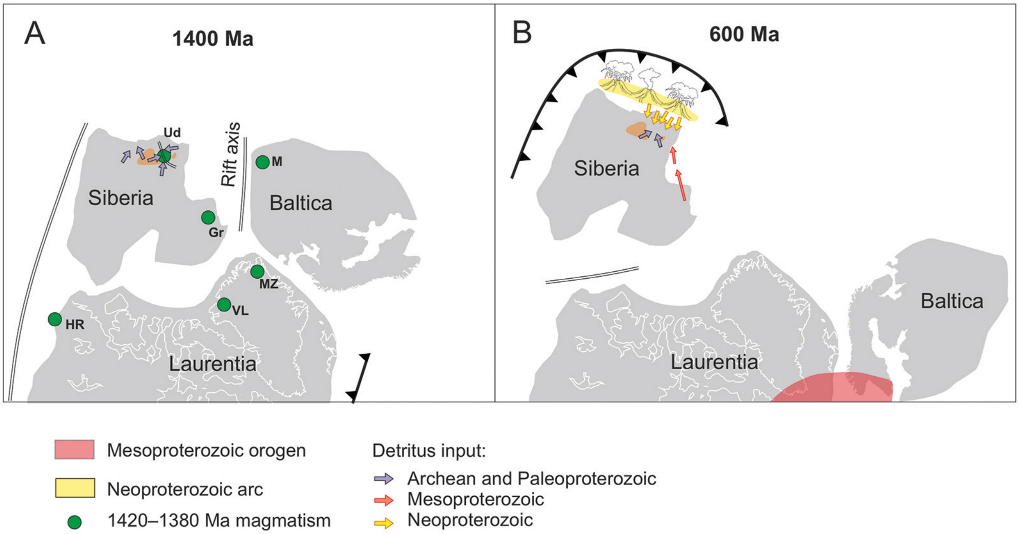

Fig. 9. (A) Reconstruction at ca. 1400 Ma with location of Sibera, Laurentia, and Baltica, after (Zhang et al., 2012). Mesoproterozoic mafic magmatic events related to Nuna break-up: HR — Hart River sills (Verbaas et al., 2018); VL — Victoria Fjord dykes (Upton et al., 2005); Midsommersø sills and Zig-Zag Dal flood basalts (Upton et al., 2005); Gr — Gornostakh dyke (Malyshev et al., 2021); M — Mashak volcanics (Puchkov et al., 2013). Proposed rift axis on 1400 Ma from (Puchkov et al., 2013; Verbaas et al., 2018), (B) and Rodinia after break up at ca. 600 Ma (right, after (Johansson, 2014)) with possible detritus input to the Udzha basin

ject but there is a widely held view that the interior of the supercontinent was affected by extension between 1.6 and 1.3 Ga, and finally, Nuna's break-up took place around 1.3 Ga (Malyshev et al., 2021; Roberts, 2013; Rogers and Santosh, 2002; Zhao et al., 2004). Further, the fragments of Nun are amalgamated to produce Rodinia at ca. 1.1–0.9 Ga (Li et al., 2008). Nevertheless, some authors pointed out the similarity between Nuna and Rodinia configurations related to lack of large-scale plate movement during the supercontinental fragmentation and assembly. The Udzha paleorift with close-in-age mafic intrusions in the northern Siberia (Ernst et al., 2016; Priyatkina et al., 2017) reflect crust extension in this part of the Nuna, whereas the close-in-age magmatic events reported from the adjacent continental blocks, e.g. Hart River sills (Verbaas et al., 2018) and Mashak intrusions (Puchkov et al., 2013) point to almost synchronous rifting in Laurentia and Baltica respectively (proposed rift axis on Fig. 9).

The age of the crustal extension and initiation of the Udzha paleoriftis estimated according to the maximum depositional age of the volcaniclastic Unguokhtakh Formation identified by U-Pb dating of detrital zircons from tuff sandstone. Four grains yielded an age of less than 1497 Ma, and one grain with an age of 1453 Ma. The measurement errors for these grains range from 12 to 29 Ma. Considering the small number of grains in this sample, it is rather difficult to reliably establish the maximum age of sedimentation. Nevertheless, new data suggest that sedimentation began after 1459 ± 16 Ma, which determines the initiation of the Udzha paleorift basin. The upper age limit of the pre-Neoproterozoic sedimentary successions is determined by the age of a dyke of 1386 ± 30 Ma, which cross-cut the Udzha Formation. Thus, the duration of sedimentation of the Udzha paleorift basin is estimated as not more than 73 ± 46 Ma.

6.2. Provenance of the Mesoproterozoic basins

The configuration of provenance in the Udzha sequence varies from the Unguokhtakh to the Udzha Formation, but available data on the immature composition of terrigenous rocks and wide distribution of grains with angular shape, discussed in the section 2, show that the source rocks were always locater close to the sedimentary basin. It contrasts with sedimentary basin on the east margin of the Anabar Shield, where mature quartz sandstones are widely distributed in the stratigraphic section implying long transport of detrital material or reworking of older sediments.

Sediment sources at the Mukun and Unguokhtakh time. At the time of deposition of the Unguokhtakh Formation in the Udzha paleorift, two provenances dominated, the detrital material of which was characterized by Paleoproterozoic (1850–1950 Ma) and Neoarchean (2500–2800 Ma) ages. For the Mukun Group, most detrital zircons are 1900–2050 Ma in age, although minor peaks at 1720 Ma, 2700–2750 Ma and 2900–2950 Ma are also recorded (this study; Kuptsova et al., 2015; Priyatkina et al., 2017). The Neoarchean age is characteristic of the basement of the northern Siberian Craton and is associated with the first phase of granulite metamorphism of the Archean blocks that form the basement, whereas older grains likely represent magmatic events (Gusev et al., 2012). The second stage of granulite metamorphism occurred in 2050–1970 Ma, which marks terrane accretion and collisional events in the Khapchan zone (Donskaya, 2020; Donskaya and Gladkochub, 2021; Priyatkina et al., 2020). These ages are characteristic of the detrital zircons in the basin framing the Anabar Shield, but are completely absent in the Udzha paleorift basin, which means that the Udzha and east Anabar basins were separated from each other and the Udzha paleorift basin did not receive clastic material from the western regions.

The peak with an age of 1850–1950 Ma is typical for the Unguokhtakh Formation detrital zircon age distribution. In turn, those ages are not typical for the crystalline basement of the northern part of the Siberian Craton, and are quite rare among the detrital zircons of the Mukun Group. However, in the southern part of the Angara belt (southwest of the Siberian Craton), they characterize the post-collision magmatism dated as 1840–1880 Ma (Donskaya and Gladkochub, 2021). The transport of detrital material from the southwestern part of the craton to the north is unlikely and, considering the local sediment sources for the Udzha paleorift basin, the source rock with the indicated age should be located within the study area. To date, there is no direct evidence of the presence of granite intrusions with a similar age in the northeastern part of the Siberian Craton. Therefore, we suggest that it may be associated with the Paleoproterozoic Khapchan orogenic zone and possible post-collision magmatism within it. This source rock was probably exposed for a short time at the first stage of development of the Udzha paleorift and relatively quickly eroded since its participation in the formation of the later Udzha Formation was not recorded.

The youngest source of 1450–1500 Ma is also considered local, and is associated with a rift magmatic event. Directly in the volcanic part of the Unguokhtakh Formation, only the flood basalts and hypabyssal mafic sills are present, which do not contain the zircons. The zircon grains with the corresponding age have a small degree of roundness, which indicates a proximal transport of detrital material. Thus, the intrusions with the indicated age are likely linked with the formation of the Udzha paleorift and were located close to the sedimentary basin of the Unguokhtakh Formation, and were felsic incomposition containing zircon.

Sediment sources at the Udzha time. The age and configuration of the provenances of the Udzha Formation strongly changed with the evolution of the Udzha paleorift. While the Unguokhtakh time was characterized by Paleoproterozoic post-collision and Neoarchean granulite basement sources, the age of detrital zircons of the Udzha Formation indicates almost exclusively the erosion of Archean granulites with an age of ca 2700 Ma. According to the studies of (Shpunt et al., 1976), the source of the terrigenous material of the Udzha Formation was composed of strongly weathered felsic rocks, and according to the paleocurrent data, the source was located to the south of the study area. These observations are consistent with the dating of detrital zircons and allow to conclude that there are local inliers of the basement within the provenance of detrital material to the Udzha basin. In contrast this source is either absent in the terrigenous deposits of the Mukun Group or has a subordinate significance (Khudoley et al., 2015; Kuptsova et al., 2015). An insignificant number of grains with an average age of 1900 Ma indicates the presence of some Paleoproterozoic rocks in the provenance.

6.3. Provenance of the Neoproterozoic basin

The sedimentation of the late Neoproterozoic (Vendian) Tomtor Formation marked a new stage in the evolution of the sedimentary basin in the north of the Siberian Platform, interrupting ~800 My gap in sedimentation between the Udzha and Tomtor formations in the Udzha basin. Together with the beginning of a new transgressive stage in the evolution of sedimentary basins which is associated with the breakup of the supercontinent Rodinia (Li et al., 2008), a new configuration of provenance are as is formed, which differs significantly from the Mesoproterozoic stage of the evolution of the region.

The age spectrum of sandstones of the Tomtor Formation contains "Siberian" signals, with peaks at 1900, 2000, 2500, and 2700 Ma, as well as single grains inheriting the age of the basement protolith (3300 Ma (Gusev et al., 2020)). Among the late Mesoproterozoic ages, there are zircons with Grenville ages (~1100 Ma) in the Tomtor Formation, which is uncommon for the basement of the Siberian Craton. Zircons with similar ages are known in the late Mesoproterozoic deposits of the Kerpyl and Ui Groups of the Uchur-Maya Plate (Khudoley et al., 2015; Podkovyrov et al., 2007) and in the Neoproterozoic sequences of the Kharayutekh Formation of the Kharaulakh Ridge (Khudoley et al., 2015), Maastakh Formation of the basin of Khorbusuonka River (Vishnevskaya et al., 2017), as well as in the southeastern Anabar region (Kuptsova et al., 2015). Their nature is explained by the erosion of the Grenville orogen in eastern Laurentia in the late Mesoproterozoic and the transportation of detrital material to the southeastern margin of Siberia since both continents were part of the Rodinia supercontinent (Ernst et al., 2016; Khudoley et al., 2015). Subsequently, the recycling of Mesoproterozoic sandstones took place with the transportation of detrital material to the northern part of the Siberian platform.

The largest peak observed in three sandstone samples of the Tomtor Formation with an age of 709 Ma is typical of the entire late Neoproterozoic sedimentary basin in the northeast of the Siberian Platform. A provenance with a similar age was recorded in the Maastakh Formation of the Olenek uplift (Vishnevskaya et al., 2017), in the Kharautekh Formation of the Kharaulakh Ridge (Khudoley et al., 2015), and in the Kysylayakh Formation exposed by the Ust-Olenek well (Priyatkina et al., 2017), which indicates the existence of a single sedimentary basin in the northeastern part of the Siberian Platform in the late

Neoproterozoic. The dominant source with this age is associated with active marginal and collisional magmatism common in the northern part of the Siberian Craton in accordance with the Neoproterozoic reconstructions of Rodinia (Li et al., 2008; Metelkin et al., 2015; Vernikovsky et al., 2013).

7. Conclusions

As a result of U-Pb dating of detrital zircons from Meso- and Neoproterozoic sandstones and volcaniclastic rocks from the basin of the Udzha River and northwestern Anabar Shield region the following results were obtained.

The maximum depositional age of the Unguokhtakh Formation and the initiating of the Udzha paleorift, according to the youngest detrital zircons age, was estimated as 1459 ± 16 Ma. Combining with the age of dyke (1386 ± 30 Ma) that cross-cut rocks of the Udzha Formation and constrain the upper limit of its deposition, the duration of the evolution of the Udzha paleorift is estimated as less than 73 ± 46 Ma.

The Udzha paleorift was an isolated sedimentary basin with local sources. The source age and configuration was distinct from that of other sedimentary basins of the northern part of the Siberian Platform.

During the evolution of the Udzha paleorift basin, a unique provenance with an age of 1850–1950 Ma associated with post-orogenic magmatism in the Khapchan collisional zone was identified.

The maximum depositional age at 564 Ma for Tomtor Formation was established. The depositional gap between the Udzha and Tomtor formations is estimated as more than 800 My.

The provenance with the source of ~700 Ma was dominated in the late Neoproterozoic on the entire northeastern margin of the Siberian Platform and is associated with continental arc magmatism on the northern margin of the Siberian platform.

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Каков возраст Уджинского палеорифта? U-Pb возраст обломочных цирконов терригенных пород Уджинского бассейна, север Сибири*

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Уджинский палеорифт, располагающийся между реками Анабар и Оленёк, является ключевой структурой, свидетельствующей о распаде суперконтинента Нуна. Вопрос о возрасте активизации и времени существования палеорифта до сегодняшнего дня не определен. В данной работе мы приводим новые данные U-Pb датирования обломочных цирконов из терригенных и вулканогенно-осадочных толщ Уджинского разреза (унгуохтахской и уджинской свит), из терригенных пород, перекрывающих Уджинский бассейн (томторская свита), и песчаника нижнерифейской мукунской серии Северо-Западного Прианабарья. Результаты датирования показывают, что начало заполнения Уджинского рифта произошло не ранее чем 1459 млн лет назад, а время активности рифта оценивается не более чем 73 млн лет. Установлено, что Уджинский бассейн являлся изолированным от окружающих бассейнов северной части Сибири и обломочный материал поступал из локальных источников сноса. Преобладающий возраст источников в Уджинском бассейне оценивается в 1.9–2.0 и 2.5–2.7 млрд лет со значительным преобладанием последнего. Напротив, в Западном Прианабарье доминирует палеопротерозойский источник с возрастом 1.9 млрд. Так же для Уджинского бассейна выявлен ранее неизвестный источник сноса с возрастом 1850 млн лет, соответствующий по времени палеопротерозойскому посторогенному магматизму Сибирской платформы. В неопротерозое поступление обломочного материала происходило с северо-востока, а источником сноса являлись активноокраинные и коллизионные магматические комплексы неопротерозойского возраста (~700 млн лет). Максимальный возраст осадконакопления Томторской свиты оценивается в 564 млн лет по самой молодой популяции цирконов, что предполагает перерыв в осадконакоплении на севере Сибири в мезо- и неопротерозое более чем в 800 млн лет.

Ключевые слова: Уджинский палеорифт, Сибирь, мезопротерозой, неопротерозой, источники сноса, U-Pb датирование, обломочные цирконы, Нуна, Родиния.

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