ISSN 0016-8521, Geotectonics, 2019, Vol. 53, No. 4, pp. 485–499. © Pleiades Publishing, Inc., 2019.
Russian Text © The Author(s), 2019, published in Geotektonika, 2019, No. 4.

A Reconstruction of a Vendian–Cambrian Active Continental Margin within the Southern Urals: Results of Detrital Zircons Studying from Ordovician Terrigenous Rocks

A. V. Ryazantsev[a, *], N. B. Kuznetsov[a, c], K. E. Degtyarev[a], T. V. Romanyuk[b, c], T. Yu. Tolmacheva[d], and E. A. Belousova[e]

[a]*Geological Institute, Russian Academy of Sciences, Moscow, 119017 Russia*
[b]*Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, 123242 Russia*
[c]*Russian State University of Oil and Gas, Moscow, 11991 Russia*
[d]*Karpinsky Russian Research Geological Institute (VSEGEI), St. Petersburg, 199106 Russia*
[e]*Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS/GEMOC), Macquarie University, Sydney, 2109 Australia*
**e-mail: avryazan51@mail.ru*

Received March 25, 2018; revised March 11, 2019; accepted March 26, 2019

Abstract—Detrital zircons of Ordovician terrigenous sequences are studied in various Southern Uralian tectonic units. The age of detrital zircons of the West Uralian and Transuralian megazones, Taganai–Beloretsk Zone, and Kraka allochthons spans from the Late Archean to the end of the Vendian– beginning of the Cambrian; Early Precambrian and Early–Middle Riphean zircons are the most abundant. Vendian–Cambrian detrital zircons are strongly dominant in the Uraltau Zone, Sakmara allochthons, and East Uralian Megazone; the zircons of other ages are absent or extremely rare. The Vendian–Cambrian detrital zircons of all Southern Urals zones probably derive from volcanic and granitic rocks of the marginal continental belt, which are part of the Uraltau Zone, Sakmara allochthons, and East Uralian Megazone. The Lu–Hf isotopic characteristics of Vendian–Cambrian detrital zircons indicate that their parental rocks formed on a heterogeneous basement that includes blocks of juvenile and ancient continental crust. According to a model of the pre-Ordovician tectonic evolution of the Southern Urals, at the end of the Late Riphean, the passive margin of the East European Platform collided with a block on a heterogeneous basement. The formation of the block terminated with the Grenville Orogeny. After collision, a volcano-plutonic belt originated in the Vendian–Cambrian at the actively evolved margin of the East European Platform.

Keywords: detrital zircons, U–Pb dating, Lu–Hf isotopic features, continental margin, suprasubduction volcanic belt, Riphean, Vendian, Ordovician, Southern Urals

DOI: 10.1134/S0016852119040058

INTRODUCTION

New isotopic-geochemical and geochronological data on various igneous, sedimentary, and metamorphic complexes of the Southern Urals have significantly expanded the concepts on the evolution of this region. At the same time, many questions of its geological structure and geodynamics are still a matter of debate, first of all, its pre-Ordovician evolution. The pre-Ordovician complexes are the most abundant and best studied in the west of the Southern Urals (Fig. 1), where they did not undergo any significant Paleozoic reworking, the reference Riphean and Vendian sections have been described in detail, their age has been substantiated, the composition of sedimentary and igneous complexes has been identified, and the formation conditions have been established [34]. The Riphean and Vendian complexes of the western tectonic units of the Southern Urals formed at the margin of the East European Platform (EEP) on the Early Precambrian basement [40]. In the central and eastern tectonic units of the Urals, the pre-Ordovician complexes were subjected to intense Middle–Late Paleozoic reworking related to overthrusting island arc and ophiolite complexes, granitic magmatism, and zonal metamorphism. These processes significantly complicate, and often make impossible, the study of the structure and composition, as well as the identification of the age and formation conditions, of pre-Ordovician complexes in these tectonic units. The different levels to which the complexes of the western and eastern tectonic units have been studied lead to contradictory models of its geodynamic evolution. Based on the Precambrian age of zircons from a set of metamorphic complexes from the eastern tectonic units, they are considered fragments from the crystal basement of the eastern margin of the EEP [22, 25, 26]. Another interpretation is that Precambrian gneiss complexes of the eastern zones of the Southern Urals are the basement of a microcontinent that accreted to the EEP in the Paleozoic [39].

Along with pre-Ordovician successions, nearly all Southern Ural tectonic units host terrigenous or terrigenous-volcanic sequences of Early to Middle–Late Ordovician age (Fig. 2). In the western tectonic units of the Southern Urals, these successions unconformably overlie Riphean and Vendian complexes. In the central and eastern tectonic units, Ordovician terrigenous successions occur above rocks considered Precambrian and Cambrian, which locally exhibit stratigraphic relationship. The Ordovician rock units underwent much less Middle–Late Paleozoic alteration than the underlying complexes, allowing more confident determination of their age, composition, and formation conditions, which are mostly believed to be related to rifting processes in the continental margin [39].

The aim of this paper is to interpret the pre-Ordovician evolution of the Southern Urals by studying the age and Lu–Hf isotopic composition of detrital zircons from Ordovician sandstones sampled in all Southern Ural tectonic units. Analysis of the results is based on available data on the structure, composition, and age of pre-Ordovician complexes of various structural zones. This comprehensive approach allowed us to interpret some pre-Ordovician structures, the complexes of which remain only locally or have not yet been identified, and to propose a model for the geodynamic evolution of the Southern Urals in the Late Riphean–Cambrian.

STRUCTURES OF THE SOUTHERN URALS AND SAMPLING OF ORDOVICIAN COMPLEXES

Several longitudinal megazones are distinguished in the Paleozoic structure of the Southern Urals: West Uralian, Central Uralian, Tagil–Magnitogorsk, East Uralian, and Transuralian (Fig. 1). All megazones (except for the Tagil–Magnitogorsk) exhibit features of pre-Cambrian continental crust, which was the basement for the Lower Paleozoic terrigenous and volcano-sedimentary successions. In the structure of these tectonic units, the Precambrian and overlying Lower Paleozoic complexes, as a rule, make up the cores of antiforms, whereas synform structures are formed by allochthons with continent-to-ocean transition complexes including ophiolites.

West Uralian Megazone

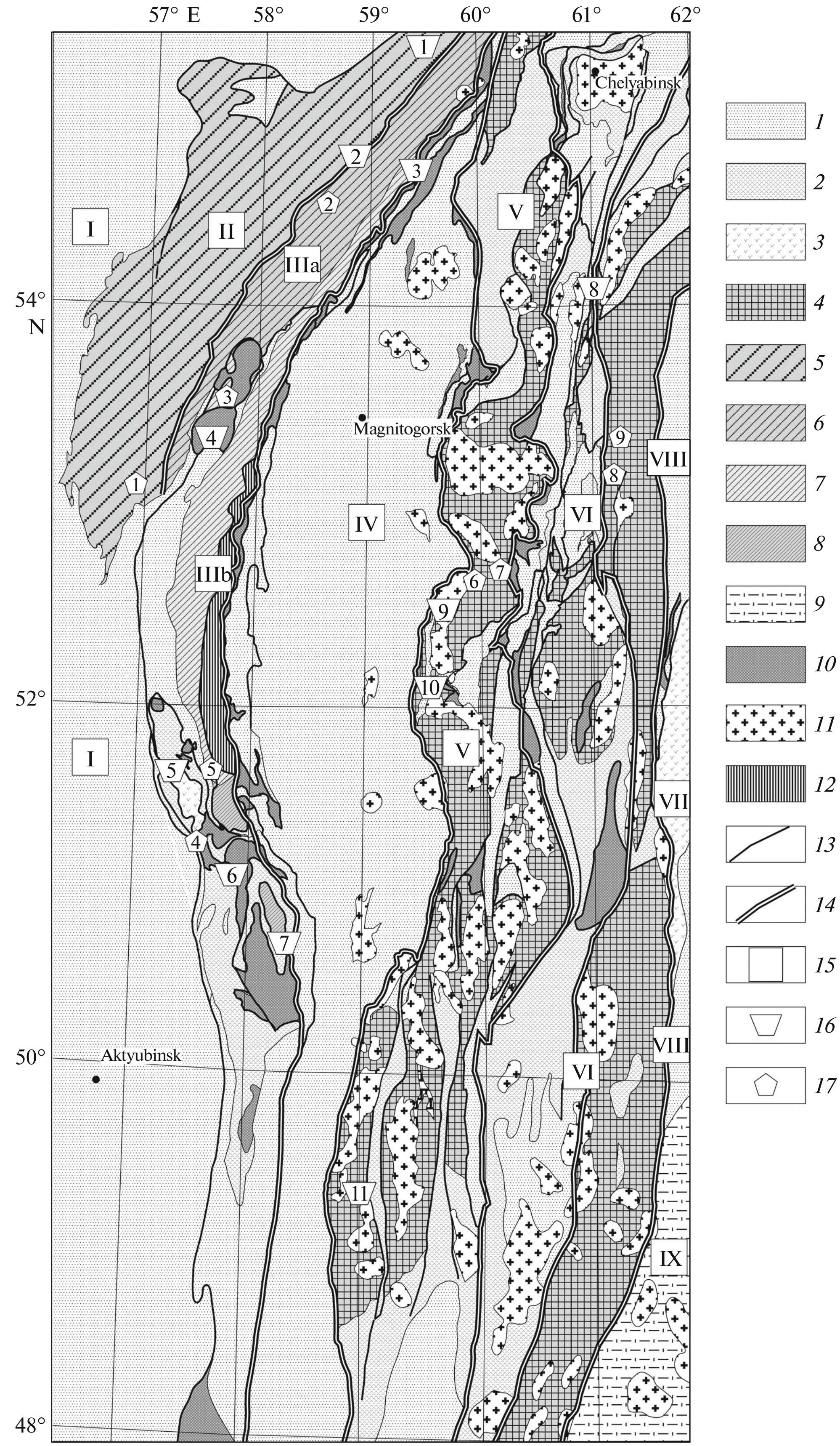
The West Uralian Megazone includes part of the Bashkirian Meganticlinorium located to the west ward of the Zyuratkul Fault. The megazone hosts Early Precambrian and Late Precambrian–Paleozoic rock units divided by a structural unconformity.

The Early Precambrian rock units include the Taratash metamorphic rock unit, which is an basement outcrop of the Volga–Uralian part of the EEP. It hosts crystalline schists and plutonic rocks, which underwent granulitic metamorphism and further diaphtoresis. The age of the rock protoliths and their metamorphic transformations varies from 3.5 to 1.8 Ga [40, 52, 73].

The Late Precambrian–Paleozoic rock units include a deformed part of the cover of the EEP and consist mostly of sedimentary rocks.

The lower part of the cover comprises a stratotypical Riphean Super Group up to 10 km thick with dominant terrigenous and carbonate rocks and mafic and felsic volcanic rocks at the Lower and Middle Riphean levels [21, 34, 36, 40, 44, 54]. The Riphean rocks are intruded by rapakivi granites dated at ~1370 Ma [40, 45]; the Taratash rock unit hosts mafic–ultramafic intrusions 726 ± 13 Ma in age [17]. The Riphean rocks exhibit metagenesis and greenschist metamorphism with a K–Ar age of 649–513 Ma [2, 34].

Fig. 1. Scheme of structural zoning and occurrence of Paleozoic and pre-Paleozoic complexes of Southern Urals (without Mesozoic–Cenozoic cover). Lithotectonic zones: I, Cisuralian marginal trough; II, West Uralian Megazone; III, Central Uralian Megazone (IIIa, Taganai–Beloretsk Zone; IIIb, Uraltau Zone); IV, Magnitogorsk Megazone; V, East Uralian Megazone; VI, Transuralian Megazone; VII, Denisovskaya Zone; VIII, Valer'yanovskaya Zone; IX, Borovskaya Zone. Individual structures and areas of study: 1, Taratash Anticlinorium; 2, Zyuratkul Fault; 3, Main Uralian Fault; 4, Kraka allochthons; 5, Blyava Synform; 6, Sakmara allochthon; 7, Ebety Antiform; 8, Sanarka River; 9, Suunduk pluton; 10, settlement of Kvarkeno; 11, Taldy Anticlinorium of Mugodzhary. Arbitrary notes: (*1*) various facial Devonian–Early Permian rocks; (*2*) Lower–Middle Paleozoic sedimentary and volcanic complexes (in east, within halo of amphibolite and greenschist metamorphism); (*3*) Late Ordovician (in west) and Early Ordovician (in east) basalt–rhyolite complex associated with ophiolites; (*4*) Precambrian and Paleozoic rocks unspecified in structure of gneiss–migmatite complexes and halos of amphibolite and greenschist metamorphism; (*5*) weakly metamorphosed Precambrian complexes and conformably overlapping unspecified Paleozoic terrigenous-carbonate sequences; (*6*) Precambrian metamorphic complexes and unconformably overlapping Ordovician–Devonian unspecified terrigenous–carbonate sequences; (*7*) Precambrian (?) and Paleozoic unspecified terrigenous sequences with greenschist facies metamorphism; (*8*) Vendian basalt–andesite–dacite–rhyolite sequences; (*9*) Middle Ordovician–Middle Devonian terrigenous sequences; (*10*) ophiolites and serpentinite mélange; (*11*) Middle–Late Paleozoic granitic rocks; (*12*) Maksyutovo eclogite–glaucophane–schist complex; (*13*) tectonic contacts; (*14*) boundaries of lithotectonic zones; (*15*) lithotectonic zones; (*16*) individual structures; (*17*) sampling points of Ordovician sandstones: 1, K12-025; 2, K12-006; 3, R14-336; 4, R09-085 and K07-007; 5, R14-396; 6, R14-228; 7, R14-310; 8, R14-355-1; 9, R14-360.


57° E
58°
59°
60°
61°
62°
54°
N
52°
50°
48°
Chelyabinsk
Magnitogorsk
Aktyubinsk
I
II
IIIa
IIIb
IV
V
VI
VII
VIII
IX
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

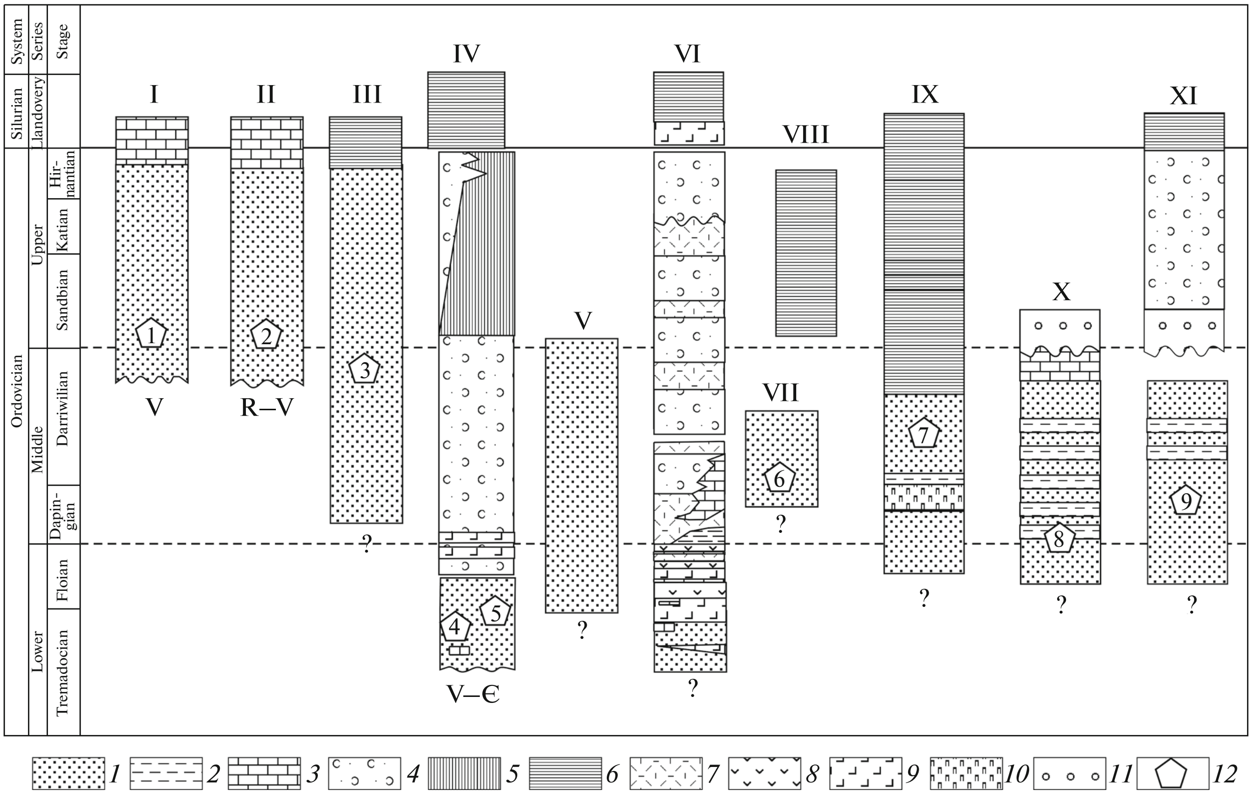


Fig. 2. Correlation of Ordovician sequences of Southern Urals and position of sampling sites for zircons. Areas of stratigraphic sections are indicated. I, West Uralian Megazone; II–VI, Central Uralian Megazone and marginal allochthons: II, Taganai–Beloretsk Zone; III, Kraka allochthons; IV–VI, Sakmara allochthon and adjacent Uraltau Zone: IV, Tyrmyntau Ridge, village of Kidryasovo; V, Bashkalgan Creek; VI, Kuagach River, Torangul Creek; VII–IX, East Uralian Megazone: VII, settlement of Rymnikskii; VIII, settlement of Kvarkeno, Novy Orenburg quarry; IX, Mt. Mayachnaya; X–XI, Transuralian Megazone: X, Kartaly-Ayat River; XI, Srednii Toguzak River. Arbitrary notes: (*1*) sandstones; (*2*) silty sandstones, siltstones; (*3*) limestones; (*4*) tuffaceous sandstones and siltstones; (*5*) siliceous tuffites; (*6*) carbonaceous schists, cherts; (*7*) rhyolites, dacites and their tuffs; (*8*) andesites, trachyandesites and their tuffs; (*9*) basalts, trachybasalts, trachyandesites, and their tuffs; (*10*) picrites; (*11*) conglomerates, tuffaceous conglomerates; (*12*) sampling points of Ordovician sandstones (numbers correspond to Fig. 1).

The Asha Group of clastic and clay rocks up to 1.5 km thick occurs upsection, with an unconformity and deep erosion [33, 40]. Its age is traditionally accepted as Vendian [40] despite the available Rb–Sr age of glauconite (638 ± 10 Ma) from the lower horizons of the group [11] and the U–Pb age of zircons (548 ± 3 Ma) from tuffs of its upper part [71]. Thus, the age of the Asha Group spans the Latest Riphean–Vendian. In addition, there are data on the possible movement of its upper boundary to the Lower Cambrian horizons [29, 69].

In the south of the megazone, rocks of the Asha Group are overlain by quartz sandstones and dolomites of the Upper Ordovician Nabiulla Formation 20–30 m thick with a parallel unconformity and conglomerates in the basement. The Formation is overlined by Silurian–Lower Devonian carbonate rocks (Fig. 2) [8]. For U–Pb geochronological studies of detrital zircons, we took sample K-12-025 from sandstones of the lower part of the formation on the right bank of the latitudinal stream of the Belaya River, west of the village of Maksyutovo (53°00′29.3″ N, 56°56′36.4″ E).

Central Uralian Megazone and System of Allochthons

The Central Uralian Megazone includes most of the Bashkirian Meganticlinorium located to the east of the Zyuratkul Fault, which has been identified as the Taganai–Beloretsk tectonic unit, and the Uraltau tectonic unit. This megazone also hosts the Sakmara and Kraka allochthons, which napped from the east (in present-day coordinates) and consist of various facial Vendian and Paleozoic complexes of the continent-to-ocean transition zone.

Taganai–Beloretsk Tectonic Unit

Early Precambrian rocks of the Aleksandsrovskii complex are considered the oldest in this zone [46]. The higher structural position is occupied by dislocated carbonaceous quartz graphite-bearing muscovite–chlorite–quartz schists and marbles, which are comparable with Riphean complexes of the West Uralian Megazone. The Upper Riphean rocks are overlain, with an erosion unconformity, by terrigenous rocks similar to the lower formations of the Vendian

Asha Group [33]. The Precambrian rocks are cut through by various intrusive rocks 1350–510 Ma in age [40, 58, 60, 64]. In the eastern part of tectonic unit, Precambrian rocks underwent high-pressure (with the formation of eclogites) metamorphism (Beloretsk complex) with an age of 515–615 Ma [2, 40, 58, 64].

Middle–Upper Ordovician terrigenous carbonate sequences of variable (20–30 to 700 m) thickness occur on Precambrian complexes with erosion and angular unconformity. The thickest section is described in the Yuryuzan Syncline with the Bakty Formation composed of quartz sandstones, conglomerates, gravelites, and calcareous sandstones [8, 62]. Sample K-12-006 consisting of quartz sandstones was taken for geochronological studies of detrital zircons from the lower part of the Bakty Formation in the southeastern limb of the Yuryuzan Syncline, on the right bank of the Tyulyuk River (53°36′21.2″ N, 58°46′57.3″ E).

Uraltau Tectonic Unit, Sakmara and Kraka Allochthons

Abundant mica–chlorite–plagioclase–quartz schists, quartzites, quartzite sandstones, and dolomites occur in the north of the Uraltau tectonic unit and are considered stratigraphic analogs of the sequences of Riphean complexes of the Bashkirian Meganticlinorium [4]. The igneous rocks include metavolcanic mafic and felsic rocks (Arsha Group of the end of the Upper Riphean, 730–705 Ma), Late Riphean gabbro–granite (730–705 Ma) and pyroxenite–gabbro (680 ± 3 Ma) complexes [20, 23, 24, 40].

The southern part of the Uraltau tectonic unit is mostly comprised of the Suvanyak and Maksyutovo schist and quartzite schist complexes of Paleozoic age (and probably Precambrian for some protoliths). The Maksyutovo complex underwent multistage tectonometamorphic evolution including Devonian high-pressure metamorphism [5, 6, 12, 31, 40].

The Vendian complexes are widely abundant in the southernmost part of the Uraltau tectonic unit and in the core of the Ebety Antiform (Fig. 1). They include volcanic and volcano-sedimentary mafic and intermediate–felsic rocks of the Lushnikovka (Kayaly) Formation (591 ± 4 Ma), up to 2.8 km thick, and mylonited granites (590–543 Ma), which are unconformably overlain by the Lower Ordovician terrigenous successions. The composition of Vendian rock units indicates their formation at the active continental margin [1, 47, 50, 51].

Cambrian rocks occur only within the Sakmara allochthon (western limb of the Blyava Synform) (Fig. 1). The Cambrian succession is dominated by effusive mafic rocks, which are divided by lenses of quartz arkose and volcanomictic sandstones and limestones (Mednogorsk Formation). The age of the Formation has been constrained by findings of Early Cambrian archaeocyathids and Late Cambrian conodonts [15, 41]. The compositional features of the volcanic rocks of the Formation indicate its origination at the continental margin in rifting and probably suprasubduction settings.

The Ordovician rocks of the Uraltau tectonic unit and the system of allochthons include terrigenous and volcano-sedimentary sequences. The Karamoly Formation, with an apparent thickness of no less than 1000 m (Fig. 1), occurs in the west of the Uraltau tectonic unit at the boundary with the Sakmara allochthon in the structure of the Maksyutovo complex and conditionally is considered to be the Lower Ordovician. It is composed of metamorphosed and intensely dislocated quartz arkose and quartzite-like siltstones and sandstones. Sample R14-396 of these sandstones was taken west of the village of Bashkalgan for geochronological studies of detrital zircons (51°35′11.8″ N, 57°47′04.2″ E).

The Lower Ordovician Kidryasovo Formation, up to 1000 m thick is composed of quartz, arkose, and rare graywacke sandstones and limestones. The formation occurs unconformably on the Vendian and Cambrian complexes [18, 48] and is overlain and facially replaced by Ordovician volcanic and volcano-sedimentary sequences [3, 18, 48].

In the Kraka allochthons, the lower nappe consists of Ordovician, Silurian, and Devonian terrigenous and siliceous rocks with arkose sandstones and siltstones of the ~900-m-thick Middle–Upper Ordovician Sukholyad Formation in the basement of the section [62].

The material for geochronological studies of detrital zircons include samples of arkose sandstones of the Kidryasovo Formation on the Tyrmantau Ridge (southeast of the Kidryasovo village) (R09-085; 51°16′57.8″ N, 57°33′58.5″ E, and K07-007; 51°16′44.7″ N, 57°33′07.4″ E) and polymictic sandstones of the Sukholyad Formation in the Kraka allochthon (R14-336; 53°36′27.8″ N, 57°56′11.2″ E).

East Uralian and Transuralian Megazones

The presence of Precambrian and Lower Paleozoic complexes in the eastern tectonic units of the Southern Urals is a matter of debate. These tectonic units were subjected to intense Middle–Late Paleozoic granitic magmatism and host abundant gneiss–migmatite and amphibolite–gneiss–schist complexes, the formation of which is mostly related to Paleozoic metamorphism [13, 56, 66]. At the same time, the possible presence of Precambrian rocks within migmatized paragneisses is evident from Early Cambrian, Vendian, and older (up to Archean) detrital zircons [30, 38, 70]. The Precambrian complexes are known in the south of the East Uralian Megazone (Taldy Anticlinorium of Mugodzhary): granites and granite gneisses 720, 950, 1020, and 1110 Ma in age [10]; the age of zircon monofractions from gneissic sequences is 509–689 Ma [19].

The Cambrian complexes of the Transuralian tectonic unit are known in the basin of the Ui and

Sanarka rivers (Fig. 1), where they include sandstones, phyllites, and lenses of limestones (Sanarka succession) with Early Cambrian archaeochyates [32]. The underlying stratigraphical succession is made up of carbonaceous–siliceous schists, phyllites, and small-grained sandstones with interlayers of limestones and Lower Cambrian oncolites, algae, and protoconodonts [38]. The Sanarka succession and underlying rocks are unconformably overlain by Ordovician terrigenous rocks.

The presence of Cambrian and Lower Ordovician complexes has recently been proved in the central part of the East Uralian Megazone: close to the eastern contact of the Middle–Late Paleozoic Suunduk granitic pluton (Fig. 1). The host rocks include granitic gneisses with garnet-bearing paragneisses, crystalline schists, and quartzites, which are combined into the Kusakan Formation, earlier ascribed to the Riphean [16, 38]. The tuff–terrigenous rocks corresponding to high-Al andesites and dacites are probably protoliths of paragneisses with a U–Pb (SHRIMP II) age of 529 ± 6 Ma. Granite gneisses with a U–Pb (SHRIMP II) age of 478 ± 5 Ma belong to calc-alkaline series and are close to volcanic arc granites in composition [49]. The Sm–Nd monomineral isochrones of gneisses of 463 ± 40 and 460 ± 7 Ma characterize the age of metamorphism [7]. The Cambrian section of this area terminated with the Chulaksai Formation of micaceous–carbonaceous–siliceous and quartzite schists and quartz–chlorite and micaceous graphite phyllites with interlayers of quartzites and marbles, which conformably overlie the Kusakan Formation. The Lower Ordovician terrigenous rocks of the Rymnik Formation unconformably occur upward and host a basal horizon of conglomerate-breccias [32].

The base of the Ordovician stratigraphical succession of the East Uralian Megazone includes graywacke, rare quartz–feldspar sandstones, gravelites, and schists of the Rymnik Formation 500–2000 m thick, the age of which is conditionally accepted as Early Ordovician [53]. Further, the succession is upbuilt by quartz–feldspar and polymictic sandstones and siltstones of the Middle Ordovician Mayachnaya Formation 300–400 m thick [3]. Its terrigenous rocks gradually give way to light gray coarsely layered cherts with Middle Ordovician conodonts [14] and Early Silurian conodonts and graptolites [49]. These rocks can be ascribed to the Novy Orenburg Formation described in the quarry near the settlement of Kvarkeno, the section of which contains Middle Ordovician [14] and Upper Ordovician [49] conodonts. For geochronological studies, samples with detrital zircons were taken from sandstones of the Rymnik Formation south of the settlement of Rymnikskii (R14-310; 52°29′50.9″ N, 60°10′02.3″ E) and sandstones of the Mayachnaya Formation at the top of Mt. Mayachnaya (R14-228; 52°31′14.4″ N, 60°15′36.5″ E).

In the Transuralian Megazone, the lower parts of the Ordovician section include porphyritic rocks of the Gorodishchenskaya Formation exposed along the Kartaly-Ayat River. Their U–Pb (SHRIMP II) age is 463–498 Ma; the older zircons (873 ± 11 and 1266 ± 16 Ma) are probably xenogenic. The formation is overlain by polymictic sandstones and siltstones of the Lower–Middle Ordovician Toguzak-Ayat Formation >1000 m thick, the stratigrphical succession of which is overlain by massive limestones with Middle Ordovician algae [14]. Rocks of the Formation also host probably Ordovician acrytarchs and scolecodonts [59]. For geochronological studies, samples with detrital zircons were taken from sandstones of the Toguzak-Ayat Formation on the left bank of the Kartaly-Ayat River (R14-355-1 and R14-360; 53°10′12.1″ N, 61°14′34.7″ E) and the Srednii Toguzak River (R14-360; 53°27′56.7″ N, 61°07′11.2″ E).

U–Th–Pb AND Lu–Hf ANALYSES OF DETRITAL ZIRCONS

The LA ICP MS U–Th–Pb age and Lu–Hf isotopic-geochemical characteristics of detrital zircons were measured on a LAM-Multi-Collector ICP mass spectrometer (HP 4500 Series 300) and a CAMEBAX SX50 electron microscope at the GEMOC Center of Macquarie University (Sydney, Australia). The methods and constants of analysis of primary data for geochronological and isotopic-geochemical study of zircons are provided in [67].

Analysis of geochronological data revealed three significantly distinct age groups of detrital zircons from (1) the West Uralian Megazone, Taganai-Beloretsk tectonic unit, and Kraka allochthon; (2) the Uraltau tectonic unit, Sakmara allochthon, and East Uralian Megazone; and (3) the Transuralian Megazone.

Samples of Group 1

These samples are dominated by Early Proterozoic and Riphean zircons (Fig. 3). The Early Proterozoic zircons, 2.1–1.7 Ga in age with bright peaks in density probability curve of 1808, 2060, 1993, 1969, and 2087 Ma, are characterized by a wide range of εHf(t) values and model ages of 2–3 Ga. The Riphean population contains grains with ages of 1.7–1.4 (peaks of 1404, 1505, 1584, 1637–1650, and 1585 Ma) and 1.3–0.9 (peaks of 1267, 1201, 976, 1072, 1232, and 1358 Ma) Ga. These zircons exhibit a wide range of εHf(t) values and model ages of 1.5–2.5 Ga. All samples contain few Late Archean–beginning of the Early Proterozoic (2.4–3.09 Ga) zircons with maxima of 2450, 2718, 2724, and 2841 and various εHf(t) values and a model age of 3.4 Ga. A striking feature of this group is a zircon population from the end of the Late Riphean–the Earliest Cambrian (536–850 Ma) with clear maxima of 536, 561–565, 570, 573, 603, 624, 656–658, 722, and

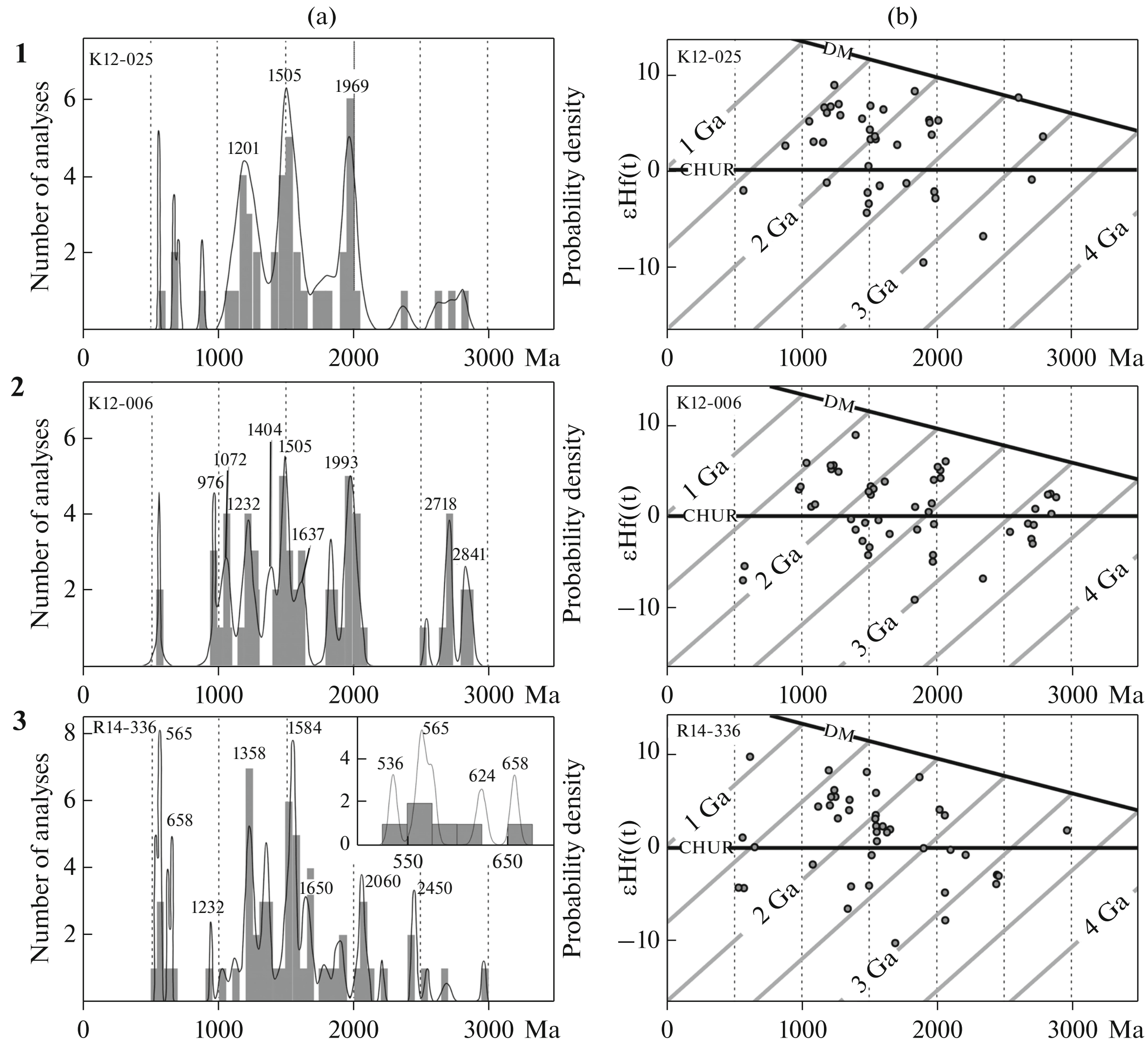


Fig. 3. Histograms and probability density plots of age distribution of detrital zircons for 500–700 Ma (right) (a) and εHf–age plots (b) for detrital zircons of Ordovician sandstones of West Uralian Megazone (sample K12-025), Taganai–Beloretsk Zone (sample K12-006), and Kraka allochthons (sample R14-336).

822 Ma. These zircons have widely variable (from –6.9 to +10) εHf(t) values and model ages of 0.75–1.9 Ga.

Samples of Group 2

These samples are strongly dominated by a zircon population with ages of 480–670 Ma with the most bright peaks of 520, 521, 529, 530, 555, 545, 547, 609, and 653 Ma (Fig. 4). Dominant zircons with positive εHf(t) values (from 0 to +13.2) are accompanied by subordinate zircons with negative εHf(t) values (from 0 to –4.3). The ages of rare grains from the Uraltau tectonic unit and Sakmara allochthon are 1.45–1.5, 2.78 and 2.45 and 1.05, 1.4–1.5, and 2.06 Ga, respectively. Grains with ages of 1.05 and 1.45–1.5 Ga have positive εHf(t) values and model ages of 1.5 and 1.8–2.0 Ga, respectively.

Samples of Group 3

These samples demonstrate the most evident zircon population 550–730 Ma in age with maxima of 567, 590, 620, 629, 656, and 707 Ma. Zircons of this age are characterized by a wide range of εHf(t) values (from +11 to –18.6), model ages of 0.8–2.97 Ga, and strongly dominant zircons with negative εHf(t) values. The samples of this group also contain numerous older zircons. Abundant Middle–Late Riphean (815–1164 Ma) zircons with bright peaks of 852, 912, 1013 are characterized by a wide range (from +12.5 to –12) of εHf(t) values and model ages of 0.8–2.5 Ga. Sample R14-355 contains only zircons ~900 Ma in age with positive (4.5–11) εHf(t) values and model ages of 1.0–1.5 Ga. The Early Precambrian zircons include Early Proterozoic and Late Archean populations. The Early Proterozoic (1818–2251 Ma; maxima of 2013,

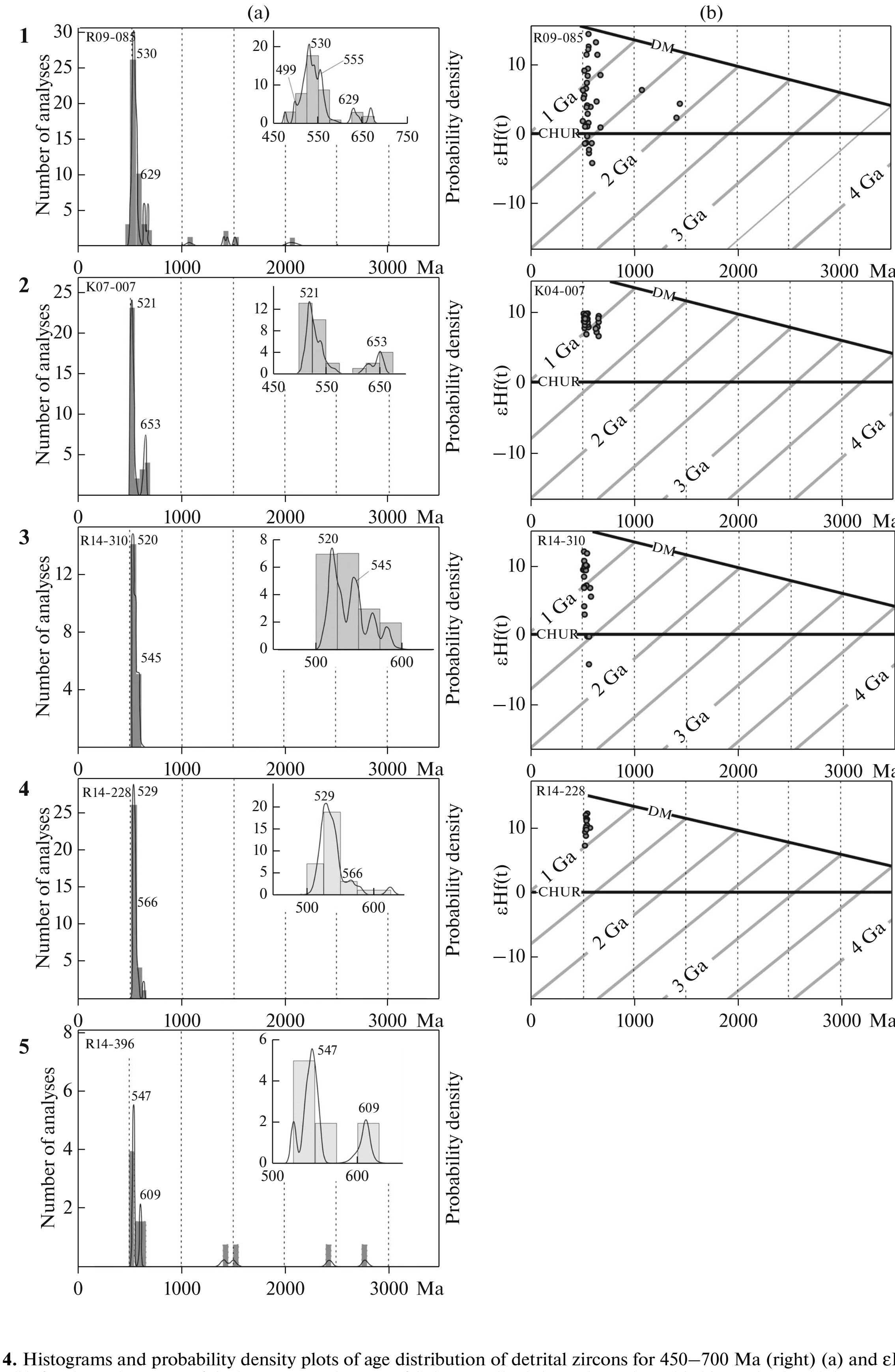


Fig. 4. Histograms and probability density plots of age distribution of detrital zircons for 450–700 Ma (right) (a) and εHf–age plots (b) for detrital zircons of Ordovician sandstones of Sakmara allochthons (samples R09-085 and K07-007), East Uralian Megazone (samples R14-310 and R14-228), and Uraltau tectonic unit (sample R14-396).

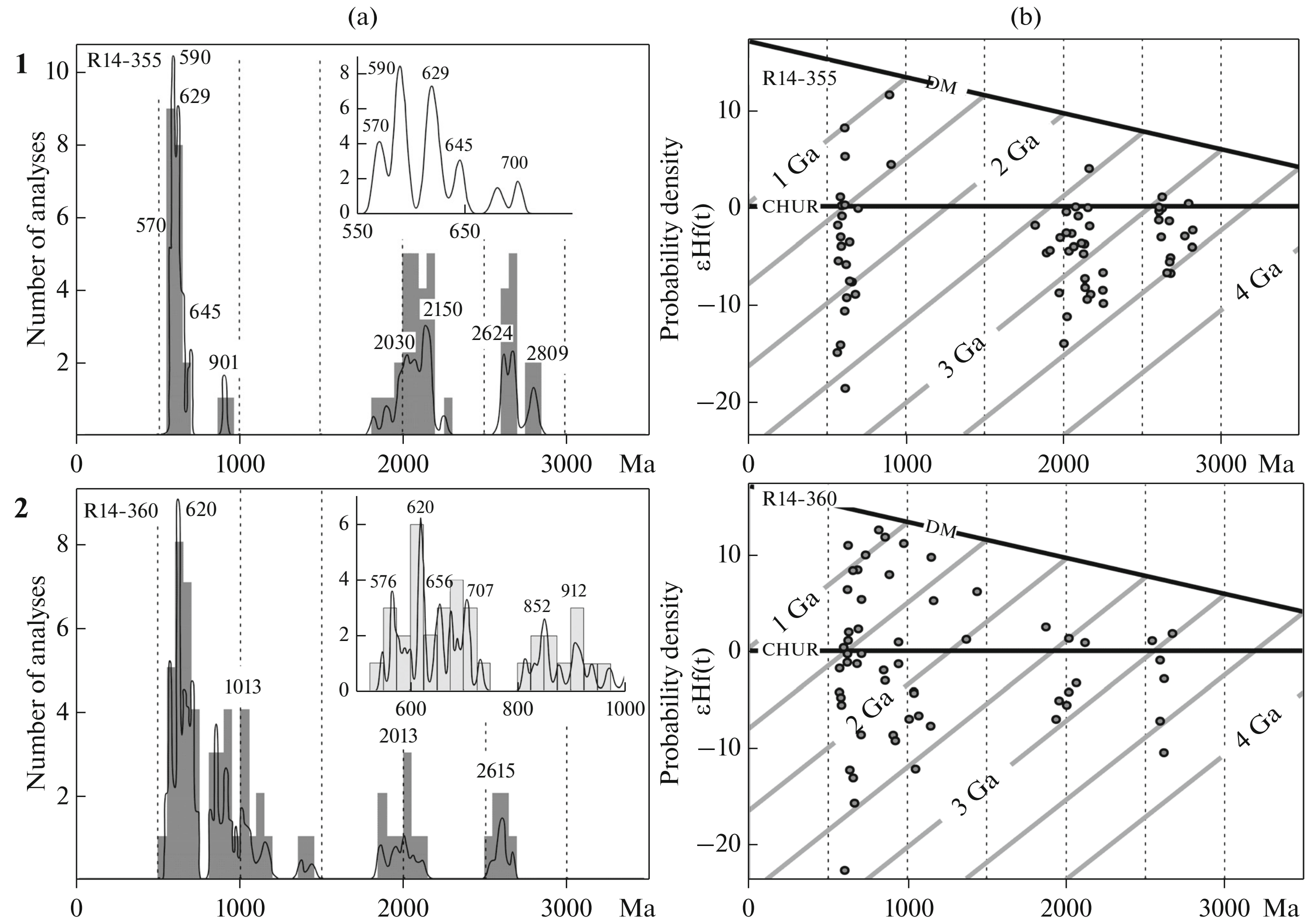


Fig. 5. Histograms and probability density plots of age distribution of detrital zircons for 500–1000 Ma (right) (a) and εHf–age plots (b) for detrital zircons of Ordovician sandstones of Transuralian Megazone (samples R14-355-1 and R14-360).

2030, 2150 Ma) and Late Archean (2543—2819 Ma; maxima of 2615, 2618, 2809 Ma) zircons exhibit mostly negative εHf(t) values and model ages of 2.4–3.4 and 3.0–3.8 Ga, respectively. Single grains of the Middle Riphean zircons (1370 and 1440 Ma), which are typical only of sample R14-360, have mostly positive εHf(t) values and model ages of 1.75 and 2.0 Ga.

POSSIBLE SOURCES OF DETRITAL ZIRCONS

The detrital zircons of Ordovician successions of various Southern Uralian tectonic units contain numerous grains from underlying Riphean and Vendian sedimentary and igneous rocks.

In group 1, the age pattern of detrital zircons is similar to those of Vendian and Riphean sequences of the West Uralian Megazone (Fig. 6) [27, 28, 35, 69]. In the Riphean, clastic material for sedimentary sequences of various parts of the Bashkirian Meganticlinorium was mostly supplied by Early Precambrian complexes of the EEP basement (detrital zircons with ages older than 1.65 Ga in Riphean sandstones) [35, 40]. Similar detrital zircons are found in Vendian [28] and Ordovician (group 1) sandstones. The formation of these zircons reflect different stages of evolution of the Volga–Uralian part of the EEP basement, which are recorded the Taratash and Aleksandrovskii complexes of the Southern Urals [40, 46, 55, 73].

In the Ordovician sandstones of the Transuralian Megazone (group 3), Early Precambrian zircons also form a significant Late Archean and Early Proterozoic population. The presence of Early Precambrian complexes within the Transuralian and East Uralian megazones is poorly substantiated. Zircons of this age occur in paragneisses with an unidentified protolith age and are probably detrital [22, 25, 30, 38, 70]. At the same time, the age ranges and isotopic characteristics of Early Precambrian zircons of the Transuralian Megazone are close to zircons of the same age in group 1. Thus, it can be suggested that the complexes of the EEP basement could have been the sources of some Early Precambrian zircons of the Transuralian Megazone.

In contrast to Riphean sandstones, Ordovician (group 1) and Vendian [28, 35] sandstones contain zircons 1400–1700 Ma in age, which could have been derived from the Early–Middle Riphean volcanic and

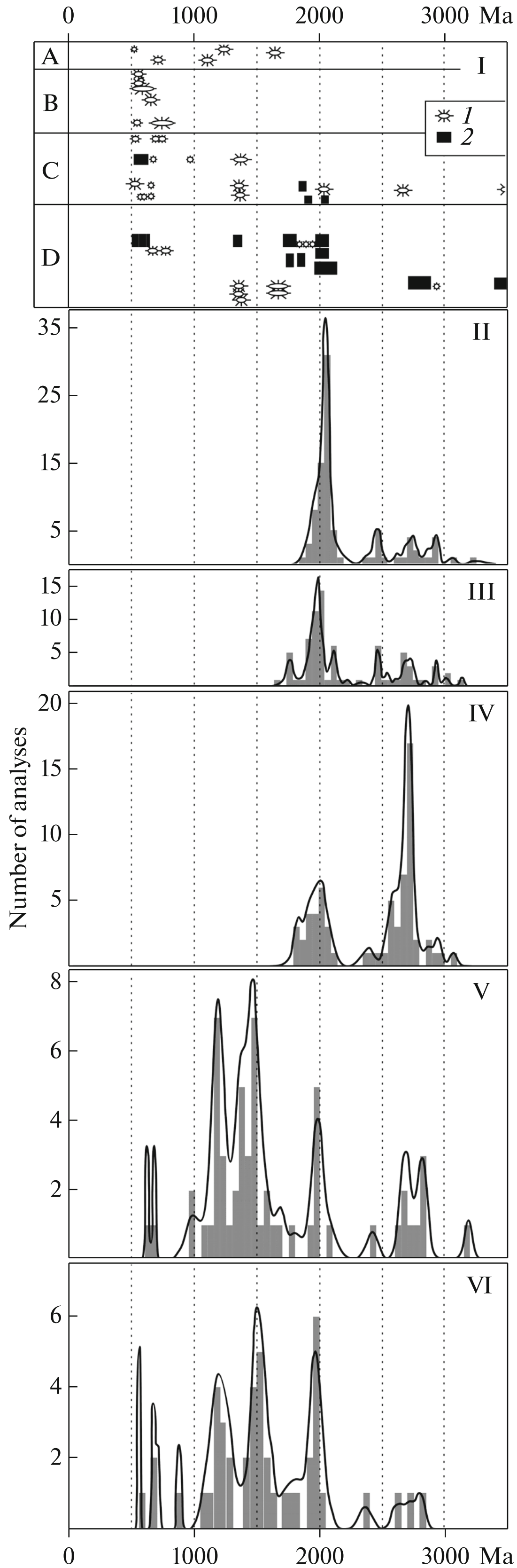


Fig. 6. Tectono-magmatic evolution of Southern Urals and its reflection in age patterns of detrital zircons in Riphean–Ordovician sandstones. I, correlation of Precambrian igneous and metamorphic complexes of the Southern Urals. A, East Uralian Megazone; B, Uraltau tectonic unit and Sakmara allochthons; C, Taganai–Beloretsk tectonic unit; D, West Uralian Megazone. 1, Period of magmatism; 2, period of metamorphism. II–VI, histograms and probability density plots of U–Pb isotopic ages of detrital zircons from Precambrian and Ordovician sandstones of the West Uralian Megazone: II, Lower Riphean Ai Formation after [35]; III, Middle Riphean Zigalga Formation after [27]; IV, Lemeza Subformation of the Upper Riphean Zilmerdak Formation after [43]; V, Upper Vendian Kukkarauk Formation after [28, 69]; VI, Middle–Upper Ordovician Nabiulla Formation.

plutonic intraplate complexes abundant in the Bashkirian Meganticlinorium [21, 36, 44, 45, 54, 58, 64]. Zircons of this age with widely variable εHf(t) values are probably evidence of mixed juvenile intraplate and ancient crustal material at their source. However, Lu–Hf isotopic characteristics of zircons in possible parental Riphean igneous rocks are currently lacking.

The Ordovician sandstones of group 1, as well as terrigenous rocks of the upper strata of the Asha Group [28, 35, 69], contain an abundant population of zircons 800–1300 Ma in age with mostly positive εHf(t) values. A similar zircon population (800–1160 Ma) with broadly variable εHf(t) values is present in one sample of Ordovician sandstones of the Transuralian Megazone.

The sources of zircons of this age is unknown within the Bashkirian Meganticlinorium and adjacent part of the EEP, since no igneous and metamorphic complexes of this period have been identified. Probably, these are granitic and metamorphic rocks of the Taldy Anticlinorium of Mugodzhary (East Uralian Megazone) with corresponding ages [10, 19]; however, these data require verification. The complexes from the end of the Middle–beginning of the Late Riphean, which could have been the sources of zircons 950–1700 Ma in age, are abundant in the Svecofennian belt of the northwestern EEP, which exhibit active accretion and collision processes during the Gothian and Grenville orogenies [63, 74]. The zircons with similar age and εHf(t) values have also been found in Upper Riphean quartzites and Lower Ordovician sandstones of the Kokchetav block of northern Kazakhstan [9, 68]. These data indicate that strongly reworked fragments of the Sveconorwegian belt occur in eastern tectonic units of the Urals and the Kokchetav block. At the same time, the Late Precambrian complexes of central and northern Australia, which could have been located close to the future Uralian margin of the EEP, are probably the sources of zircons of this age [28, 69].

The samples of Ordovician sandstones of all groups contain a relatively small zircon population

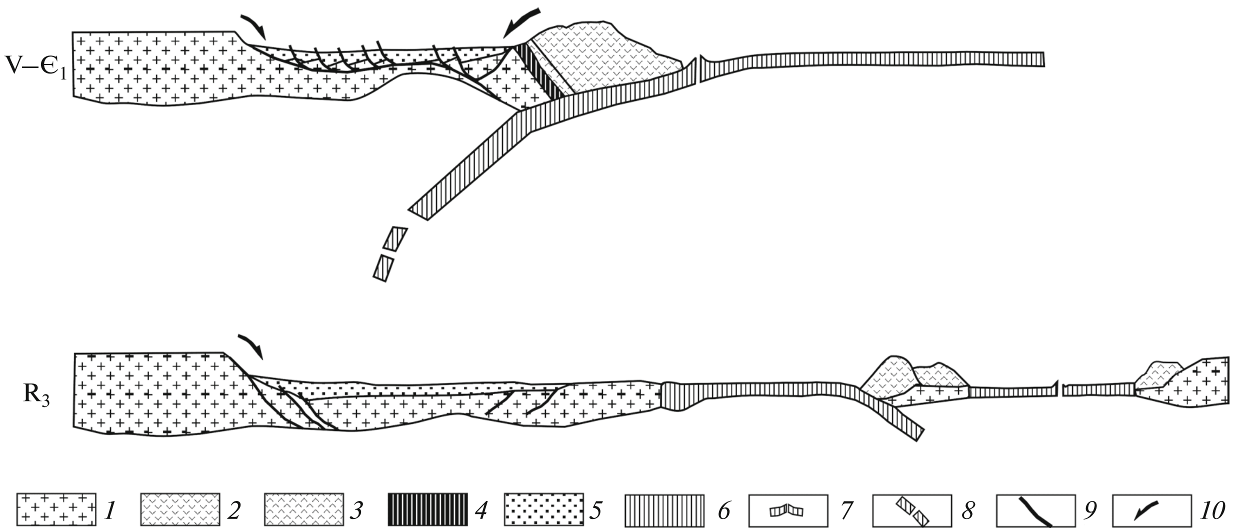


Fig. 7. Geodynamic profiles for Southern Urals paleostructures in the Riphean–Cambrian. Arbitrary notes: (*1*) Continental crust; (*2*) complexes of active intraoceanic island arcs and marginal continental volcanic belts; (*3*) accreted complexes of island arcs; (*4*) ophiolites; (*5*) terrigenous, volcanic, and volcano-sedimentary sequences of marginal continental riftogenic trough; (*6*) oceanic crust; (*7*) spreading zones; (*8*) slab fragments; (*9*) dominant directions of clastic runoff.

600–750 Ma in age with broadly variable εHf(t) values (similar zircons have been found in sandstones of the Upper Vendian Kukkarauk Formation) [28, 35, 69]. These zircons could have originated from various igneous and metamorphic rocks within the Uraltau and Taganai–Beloretsk tectonic units: Barangulovo gabbro–granite–leucogranite, Kiryabinka pyroxenite–gabbro, and Yurmaty granite complexes, dikes of diorites and trondhjemites and volcanic rocks of the Arsha Group, as well as metamorphic rocks of Beloretsk high-pressure complex [2, 20, 23, 24, 40, 58]. Igneous rocks of this age have a mostly intraplate origin [42]. Broadly variable εHf(t) values of detrital zircons are probably related to mixed juvenile intraplate and ancient crustal material at their source, although no Hf isotopic composition of zircons from possible parental rocks is known.

The presence of a zircon population 520–600 Ma in age (absolutely dominant in group 2) is a striking feature of Ordovician sandstones of all Uralian tectonic units. In group 2, zircons are characterized by positive εHf(t) values, in contrast to group 3 with mostly negative εHf(t) values. These zircons could have derived from Vendian and Cambrian marginal continental igneous complexes, which are abundant in the Uraltau tectonic unit, Sakmara allochthon, and East Uralian Megazone, and are overlain by Ordovician successions with erosional unconformity. The broadly variable Hf isotopic composition of zircons could be related to the heterogeneous basement of the Vendian–Cambrian volcanic belt, which could have included blocks of juvenile and ancient crust. The evidence of a relatively young substrate, which partly generated the metamorphic complexes of the eastern tectonic units of the Urals and then Paleozoic granitic rocks, were revealed earlier based on isotope data [13, 37, 39, 56, 57, 61, 66]. Single zircons with an age of 476 Ma in sandstones of the Kidryasovo Formation of the Sakmara allochthon could be related to Early Ordovician volcanism in this tectonic unit.

MODEL OF PRE-ORDOVICIAN GEODYNAMIC EVOLUTION OF THE REGION

The results of our studies suggest a scenario of pre-Ordovician geodynamic evolution of the Southern Urals (Fig. 7). The most important element of the model is related to the Vendian–Cambrian marginal continental volcanic-plutonic belt, the complexes of which were parental for the youngest zircon population from Ordovician sandstones of all tectonic units. Another model element, which is identified mostly on the basis of detrital zircons, is a block with Precambrian complexes which formed mostly during orogenic events which simaltaneous to the Gothian and Grenville orogenesis within Sveconorwegian area.

In the Riphean (including the late period), the EEP contained a passive Uralian margin with a pericratonic rift trough [34]. It was filled with thick carbonate and terrigenous sequences, the clastic material of which was delivered from Volga–Uralian complexes of the EEP basement. This trough exhibited episodic intraplate intrusive and effusive magmatism [40, 42].

At the end of the Late Riphean, the passive margin of the EEP began to collide with a block that consisted mostly of Middle and Late Riphean complexes. It has been suggested that, prior to collision, this block had an active margin. Collision is evident from the large hiatus and unconformity in the basement of the Asha Group. The accreted block provided detrital zircons

800–1300 Ma in age and may have also hosted older complexes that also contributed zircons. The formation of the Middle–Late Riphean complexes of this block was probably related to accretionary–collisional processes, and this block could be a fragment of the Grenville orogenic belt: it could have detached as a result of breakup of the supercontinent of Rodinia in the second half of the Late Riphean [63].

After collision, at the Latest Riphean– the Earliest Cambrian, the Uralian margin of the EEP became active, leading to the formation of the marginal continental volcano-plutonic belt. The earliest (660 ± 35 Ma) suprasubduction magmatism products could have included gabbro–diorite–trondhjemite dikes in the eastern part of Bashkirian Meganticlinorium [58] and the belt's main stage of magmatic activity corresponds to the Middle Vendian–beginning of the Cambrian (590–530 Ma) [47, 50, 51]. The eruption of rift-related volcanic rocks in the Cambrian strata of the Sakmara allochthons, which are coeval with calc-alkaline magmatism of the East Uralian Megazone, could be related to the unstable regime of the subduction zone or extensional processes in its rear part. Igneous rocks, the formation of which is related to the evolution of various parts of Vendian–Cambrian marginal continental belt, were the main sources of the youngest population of detrital zircons in Ordovician sandstones of all Uralian tectonic units.

In the Vendian, the back-arc part of the volcanic belt was the formation and exposure area of rocks of the Beloretsk high-pressure metamorphic rock unit in upper crustal level. This complex includes lower and intermediate crustal rocks, which were exhumed following the scenario of Cordilleran-type metamorphic rock complexes. The geodynamic setting of high-pressure metamorphism, however, is still unclear [2, 40, 64, 65]. The Vendian sequences of the West Uralian Megazone in the upper part of the section with clastic rocks of the Beloretsk rock unit formed as a result of syntectonic filling of rift depressions or as molasse in the back-arc part of the active margin [40].

The Vendian–Cambrian evolution of the marginal continental volcanic-plutonic belt of the Southern Urals is correlated with the evolution of the Cadomian belt [72], part of which consisted of the discussed margin.

The data on the age of detrital zircons and their Hf isotopic composition suggest that terrigenous Ordovician and underlying older complexes of all megazones belong to one continental margin at the beginning of the Ordovician.

CONCLUSIONS

Analysis of new data on detrital zircons from Ordovician terrigenous rocks of various Southern Ural tectonic units shows that the age range and features of the Hf isotopic composition of detrital zircons are mostly caused by various underlying pre-Ordovician complexes, responsible for the crustal heterogeneity of this region.

In the West Uralian Megazone, Taganai–Beloretsk tectonic unit, Kraka allochthons, and Transuralian Megazone, the age of detrital zircons ranges broadly from the Late Archean to the end of Vendian– beginning of the Cambrian with widely variable εHf(t) values. Early Precambrian and Early–Middle Riphean zircons are the most abundant. Vendian–Cambrian zircons with positive εHf(t) values are strongly dominant in the Uraltau Zone, Sakmara allochthons, and East Uralian Megazone; zircons of other ages are either completely absent or extremely rare.

Possible sources of most Early Precambrian, Early, Middle and Late Riphean detrital zircons are igneous and metamorphic complexes of the Volga–Uralian part of the EEP basement and Bashkirian Meganticlinorium. However, no complexes are known in these regions that could have been the sources of zircons 800–1300 Ma in age. It is suggested that they could have originated from rock units that formed as a result of accretionary–collisional processes during the Gothian and Grenville orogenies, counterparts of which have been found in the Sveconorwegian belt of the northwestern EEP. Fragments of a block composed of these complexes could have included the Taldy Anticlinorium of Mugodzhary and part of the Transuralian Zone. We suggest that the volcanic and granitic rocks of the marginal continental belt, which are found in the Uraltau Zone, Sakmara allochthons, and East Uralian Megazone, are the source of Vendian–Cambrian zircons from Ordovician sandstones of all Uralian zones.

These data became the basis for a model of the pre-Ordovician evolution of the Uralian margin of the EEP. It is suggested that, at the end of the Late Riphean, the passive continental margin of the EEP collided with a block on a heterogeneous basement, the formation of which terminated during the Grenville Orogeny. After collision, the passive regime was replaced by an active one, leading to the formation of the marginal continental volcano-plutonic belt. Its rear part underwent Late Vendian metamorphism and exhumation of its products, similarly to the complexes of Cordilleran-type metamorphic cores, whereas adjacent depressions were filled with molasse.

FUNDING

Synthesis and analysis of geological materials of the Southern Urals was carried out in accordance with the plans of basic research of the Geological Institute of Russian Academy of Sciences (GIN RAS, Moscow, Russia) (no. 0135-2016-0009). The study of heterogeneity of the crust of the Southern Urals, field works, isotopic analytical studies, and preparation of the paper were supported by the Russian Science Foundation (project no. 14-27-00058). Sample preparation and processing of analytical data were supported by the Russian Foundation for Basic Research (project nos. 16-05-00259 and 16-05-00519). This paper is contribution 1366 from the ARC Centre of Excellence for Core to Crust Fluid Systems (Sydney, Australia; http://www.ccfs.mq.edu.au) and 1322 in the GEMOC Key Centre (Sydney, Australia; http://www.gemoc.mq.edu.au).

REFERENCES

1. A. A. Abdulin, A. V. Avdeev, and N. S. Seitov, *Tectonics of the Sakmara and Or–Ilek Zones of the Mugodzhary Mountains* (Nauka, Alma-Ata, 1977) [in Russian].
2. A. A. Alekseev, S. G. Kovalev, and E. A. Timofeeva, *Beloretsky Metamorphic Complex* (Inst. Geol. Ural. Nauchn. Tsentra Ross. Akad. Nauk, Ufa, 2009) [in Russian].
3. N. Ya. Antsygin, "On Ordovician stratigraphy of the eastern slope of the Urals," in *Problems of Geology of Precambrian and Lower Paleozoic*, Ed. by B. A. Popov (Mingeo RSFSR, Moscow, 1985), pp. 68–86.
4. E. A. Bazhin, V. I. Snachev, A. V. Snachev, and M. V. Rykus, *Geology, Petrogeochemistry, and Ore-Bearing Potential of Granitoid Massifs of the Bashkirian Megaanticlinorium and Uraltau Zone* (Svoe izdatel'stvo, St. Petersburg, 2015) [in Russian].
5. P. M. Valizer, A. A. Krasnobaev, A. I. Rusin, "Jade–grossular eclogite of the Maksyutovo complex, South Urals," Litosfera, No. 4, 50–61 (2013).
6. P. M. Valizer, A. A. Krasnobaev, and A. I. Rusin, "UHPM eclogite of the Maksyutov complex, South Urals," Dokl. Earth Sci. **461**, 291–296 (2015).
7. V. I. Vinogradov, S. A. Shcherbakov, V. M. Gorozhanin, Yu. V. Gol'tsman, and M. I. Bujakaite, "Age of metamorphites in the Eastern Ural Uplift: Sm–Nd and Rb–Sr-isotope dating," Dokl. Earth Sci. **371**, 477–480 (2000).
8. E. N. Gorozhanina, V. M. Gorozhanin, N. B. Kuznetsov, and T. V. Romanyuk, "Peculiarities of composition and structure of Ordovician terrigenous deposits in sections of the southeastern East European Platform and South Urals," Geol. Sb. Inst. Geol. Ural. Nauchn. Tsentr Ross. Akad. Nauk, No. 11, 97–117 (2014).
9. K. E. Degtyarev, T. Yu. Tolmacheva, A. A. Tretyakov, N. B. Kuznetsov, E. A. Belousova, and T. V. Romanyuk, "Structure, age, and settings of formation of Ordovician complexes of the northwestern frame of the Kokchetav massif, northern Kazakhstan," Stratigr. Geol. Correl. **26**, 514–533 (2018).
10. *Precambrian and Lower Paleozoic of Western Kazakhstan*, Ed. by A. V. Milovskii (Mosk. Gos. Univ., Moscow, 1977) [in Russian].
11. T. S. Zaitseva, A. B. Kuznetsov, I. M. Gorokhov, G. V. Konstantinova, and N. N. Mel'nikov, "Rb–Sr age of Vendian glauconites from the Bakeevo Fm., Southern Urals," *Isotope Dating of Geological Processes: New Results, Approaches, and Perspectives; Proceedings of the VI All-Russia Conference on Isotope Geochronology* (Inst. Geol. Geokhronol. Dokembriya Ross. Akad. Nauk, St. Petersburg, 2015), pp. 94–95.
12. O. A. Zakharov and V. N. Puchkov, *Tectonic Nature of the Maksyutovo Metamorphic Complex in South Urals* (Ural. Nauchn. Tsentr Ross. Akad. Nauk, Ufa, 1994) [in Russian].
13. K. S. Ivanov, V. F. Panov, I. I. Likhanov, P. S. Kozlov, V. S. Ponomarev, and V. V. Khiller, "Precambrian of the Urals," Gorn. Vedomosti, No. 9, 4–28 (2016).
14. K. S. Ivanov, V. N. Puchkov, and I. A. Pelevin, "New data on stratigraphy and evolution of Paleozoides in the eastern zones of the South Urals," in *New Data on Stratigraphy and Lithology of Paleozoic of the Urals and Central Asia*, Ed. by K. S. Ivanov (Nauka, Yekaterinburg, 1992), pp. 3–10.
15. M. A. Kamaletdinov, *Nappe Structures of the Urals* (Nauka, Moscow, 1974) [in Russian].
16. Yu. G. Knyazev, O. Yu. Knyazeva, V. I. Snachev, A. V. Zhdanov, T. R. Karimov, E. M. Aidarov, R. Kh. Masagutov, and E. R. Arslanova, *Explanatory Note to the State Geologic Map of Russian Federation, Scale 1 : 1000000 (Third Generation). Uralian Series. Sheet N-40 (Ufa)* (VSEGEI, St. Petersburg, 2013) [in Russian].
17. S. G. Kovalev, "Geochemistry and geodynamic conditions of diabase-picrite magmatism formation on the western slope of the South Urals," Geol. Sb. Inst. Geol. Ural. Nauchn. Tsentr Ross. Akad. Nauk, No. 5, 113–118 (2006).
18. V. G. Korinevskii, *Lower Ordovician Reference Sections of the South Urals: Terrigenous Facies* (Ural. Otd. Akad. Nauk SSSR, Sverdlovsk, 1989) [in Russian].
19. A. A. Krasnobaev, V. A. Davydov, and N. V. Cherednichenko, "U–Pb age of zircons from metamorphic rocks of the Mugodzhary Mountains," in *Yearbook-1996 of the Institute of Geology and Geochemistry, Ural Branch of the Russian Academy of Sciences* (Ural. Otd. Ross. Akad. Nauk, Yekaterinburg, 1997), pp. 147–150.
20. A. A. Krasnobaev, V. I. Kozlov, V. N. Puchkov, N. D. Sergeeva, and S. V. Busharina, "New data on zircon geochronology of the Arsha Volcanic Series, South Urals," Litosfera, No. 4, 127–140 (2012).
21. A. A. Krasnobaev, V. N. Puchkov, V. I. Kozlov, N. D. Sergeeva, S. V. Busharina, and E. N. Lepekhina, "Zirconology of Navysh volcanic rocks of the Ai Suite and the problem of the age of the Lower Riphean boundary in the Southern Urals," Dokl. Earth Sci. **448**, 185–190 (2013).
22. A. A. Krasnobaev, V. N. Puchkov, B. A. Puzhakov, S. V. Busharina, and N. D. Sergeeva, "Zircon Archean of the Transuralian megazone," Dokl. Earth Sci. **465**, 1302–1307 (2015).
23. A. A. Krasnobaev, V. N. Puchkov, N. D. Sergeeva, and S. V. Busharina, "Uranium-lead age of zircons from granites and the substrate of the Mazara massif (Southern Urals)," Dokl. Earth Sci. **463**, 719–725 (2015).
24. A. A. Krasnobaev, V. N. Puchkov, N. D. Sergeeva, and E. N. Lepekhina, "Zirconology of pyroxenites from the Kiryabinka pyroxenite-gabbro complex (Southern Urals)," Dokl. Earth Sci. **450**, 531–535 (2013).
25. A. A. Krasnobaev and N. V. Cherednichenko, "Zircon geochronology of metamorphic rocks of the Mariinov complex (Southern Urals)," Dokl. Earth Sci. **404**, 1116–1120 (2005).
26. A. A. Krasnobaev, V. A. Davydov, E. P. Shchul'kin, and N. V. Cherednichenko, "Zirconology of the Sely-

ankino block in the Il'meny Mountains," Dokl. Earth Sci. **379**, 744–748 (2001).

27. N. B. Kuznetsov, E. A. Belousova, T. V. Romanyuk, K. E. Degtyarev, A. V. Maslov, V. M. Gorozhanin, E. N. Gorozhanina, and E. S. Pyzhova, "First results of U/Pb dating of detrital zircons from middle Riphean sandstones of the Zigalga Formation, South Urals," Dokl. Earth Sci. **475**, 863–867 (2017).
28. N. B. Kuznetsov, T. V. Romanyuk, A. V. Shatsillo, S. Yu. Orlov, I. V. Golovanova, K. N. Danukalov, and I. S. Ipat'eva, "The first results of mass U-Pb isotope dating (LA-ICP-MS) for detrital zircons from the Asha Group, South Urals: Paleogeography and paleotectonics," Dokl. Earth Sci. **447**, 1240–1246 (2012).
29. N. B. Kuznetsov and A. V. Shazillo, "The first finds of skeletal fossils in the Kuk-Karauk formation of the Asha Group (Southern Urals) and their significance for determining the beginning of the Pre-Uralian-Timanian orogeny," Dokl. Earth Sci. **440**, 1239–1244 (2011).
30. P. V. Lyadskii, L. N. Kvasnyuk, A. V. Zhdanov, O. V. Chechulina, N. T. Shmel'kov, G. M. Bel'ts, E. S. Kurochkina, and T. V. Olenitsa, *Explanatory Note to the State Geologic Map of Russian Federation, Scale 1 : 000 000 (Third Generation). Uralian Series. Sheet M–40 (Orenburg) with the M–41 Inset* (VSEGEI, St. Petersburg, 2013) [in Russian].
31. T. M. Mavrinskaya and R. R. Yakupov, "Biostratigraphic characteristic of the Suvanyak and Maksyutovo complexes of the Uraltau (South Urals)," *Geology, Mineral Resources and Geoecological Problems of Bashkortostan, Urals, and Adjacent Areas, Interregional Research-and-Practice Conference, Ufa, Russia, 2012* (Dizain-Press, Ufa, 2013), pp 53–55.
32. N. F. Mamaev, *Geological Structure and Evolution of the Eastern Slope of the South Urals*, Vol. 73 of *Tr. Inst. Geol Ural. Fil. Akad. Nauk SSSR* (Inst. Geol Ural. Fil. Akad. Nauk SSSR, Sverdlovsk, 1965) [in Russian].
33. A. V. Maslov, "Some specific features of Early Vendian sedimentation in the Southern and Middle Urals," Lithol. Miner. Resour. **35**, 556–570 (2000).
34. A. V. Maslov, M. T. Krupenin, E. Z. Gareev, and L. V. Anfimov, *Riphean of the Western Slope of the South Urals: Classic Sections, Sedimentogenesis, Lithogenesis, Minerageny, and Geological Natural Monuments* (Inst. Geol. Geokhim. Ural. Otd. Ross. Akad. Nauk, Yekaterinburg, 2001), Vol. 1 [in Russian].
35. A. V. Maslov, G. A. Mizens, G. M. Vovna, E. S. Pyzhova, N. B. Kuznetsov, V. I. Kiselev, Yu. L. Ronkin, A. Z. Bikbaev, and T. V. Romanyuk, "On some general peculiarities of formation of terrigenous deposits in the West Urals: A synthesis of the data on U–Pb isotope dating of detrital zircons and geochemical studies of clay rocks," Litosfera, No. 3, 27–46 (2016).
36. *Lower Riphean of the South Urals*, Ed. by M. A. Semikhatov (Nauka, Moscow, 1989) [in Russian].
37. T. A. Osipova, "Granitoid sources in the Main Granite Axis of the Urals: Sm–Nd, Rb–Sr, and U–Pb data," *Magmatism and Metamorphism in the Earth's History: Proceedings of the XI All-Russia Meeting on Petrology* (Inst. Geol. Geokhim. Ural. Otd. Ross. Akad. Nauk, Yekaterinburg, 2010), Vol. II, pp. 111–112.
38. B. A. Puzhakov, V. P. Savel'ev, N. S. Kuznetsov, V. D. Shokh, E. P. Shchul'kin, N. E. Shchul'kina, A. V. Zhdanov, O. Ya. Dolgova, E. A. Tarelkina, and M. V. Orlov, *Explanatory Note to the State Geologic Map of Russian Federation, Scale 1 : 1000 000 (Third Generation). Uralian Series. Sheet N–41* (*Chelyabinsk*) (VSEGEI, St. Petersburg, 2013) [in Russian].
39. V. N. Puchkov, *Paleogeodynamics of the South and Middle Urals* (Dauriya, Ufa, 2000) [in Russian].
40. V. N. Puchkov, *Geology of the Urals and Cis-Ural Region: Topical Problems of Stratigraphy, Tectonics, Geodynamics, and Metallogeny* (DizainPoligrafServis, Ufa, 2010) [in Russian].
41. V. N. Puchkov, "Tectonics of the Urals: Modern concepts," Geotectonics **31**, 294–312 (1997).
42. V. N. Puchkov, "Plume-dependant granite-rhyolite magmatism," Litosfera **18**, 692–705 (2018).
43. T. V. Romanyuk, A. V. Maslov, N. B. Kuznetsov, E. A. Belousova, Yu. L. Ronkin, M. T. Krupenin, V. M. Gorozhanin, E. N. Gorozhanina, and E. S. Seregina, "First data on LA-ICP-MS U/Pb zircon geochronology of Upper Riphean sandstones of the Bashkir Anticlinorium (South Urals)," Dokl. Earth Sci. **452**, 997–1000 (2013).
44. Yu. L. Ronkin, A. V. Maslov, A. P. Kazak, D. I. Matukov, and O. P. Lepikhina, "The Lower-Middle Riphean boundary in the southern Urals: New isotopic U-Pb (SHRIMP II) constraints," Dokl. Earth Sci. **415**, 835–840 (2007).
45. Yu. L. Ronkin, D. I. Matukov, S. L. Presnyakov, E. N. Lepekhina, O. P. Lepikhina, and O. Yu. Popova, "'In situ' U–Pb SHRIMP dating of zircons from nepheline syenites of the Berdyaush massif (South Urals)," Litosfera, No. 1, 135–142 (2005).
46. Yu. L. Ronkin, S. Sindern, and O. P. Lepikhina, "Isotope geology of the oldest geological units of the South Urals," Litosfera, No. 5, 50–76 (2012).
47. A. V. Ryazantsev, "Vendian suprasubdction magmatism in the Southern Urals," Dokl. Earth Sci. **482**, 1157–1160 (2018).
48. A. V. Ryazantsev and T. Yu. Tolmacheva, "Ordovician volcanic and plutonic complexes of the Sakmara allochthon in the southern Urals," Geotectonics **50**, 553–578 (2016).
49. A. V. Ryazantsev and T. Yu. Tolmacheva, "Vendian an Early Paleozoic complexes of the active continental margin in Paleozoides of the South Urals," in *Tectonics of the Modern and Ancient Oceans and Their Margins: Proceedings of the XLIX Meeting on Tectonics on the 100th Anniversary of Academician Yu. M. Pushcharovskii* (GEOS, Moscow, 2017), Vol. 2, pp. 169–172.
50. S. G. Samygin, A. A. Belova, A. V. Ryazantsev, and A. A. Fedotova, "Fragments of the Vendian convergent borderland in the South Urals," Dokl. Earth Sci. **432**, 726–731 (2010).
51. S. G. Samygin, A. A. Fedotova, E. V. Bibikova, and Yu. V. Karyakin, "Vendian suprasubduction volcanism in the Uraltau tectonic zone (South Urals)," Dokl. Earth Sci. **416**, 995–999 (2007).
52. A. I. Stepanov and Yu. L. Ronkin, "Isotope geochronology of the oldest igneous and metamorphic complexes in the zone of the Zyuratkul Fault (South

Urals)," in *Yearbook-2015 of the Institute of Geology and Geochemistry Ural Branch of the Russian Academy of Sciences* (Ural. Otd. Ross. Akad. Nauk, Yekaterinburg, 2016), pp. 178–184.

53. Al. V. Tevelev, I. A. Kosheleva, V. S. Popov, I. E. Kuznetsov, T. A. Osipova, N. V. Pravikova, and A. S. Gustova, *Paleozoides of the Junction Zone between the East Urals and Transuralian Region*, Vol. 4 of *Tr. Lab. Geol. Skladchatykh Poyasov* (Mosk. Gos. Univ., Moscow, 2006) [in Russian].
54. Al. V. Tevelev, I. A. Kosheleva, O. A. Khotylev, Ark. V. Tevelev, and I. A. Prudnikov, "Peculiarities of the structure and evolution of the Riphean Ai volcanic complex, South Urals," Moscow Univ. Geol. Bull. **69**, 289–298 (2014).
55. Al. V. Tevelev, I. A. Kosheleva, Ark. V. Tevelev, A. O. Khotylev, V. M. Moseichuk, and V. I. Petrov, "New data on the isotope ages of the Taratash and Aleksandrovka metamorphic complexes," Moscow Univ. Geol. Bull. **70**, 24–40 (2015).
56. G. B. Fershtater, N. S. Borodina, N. G. Soloshenko, and M. V. Streletskaya, "New data on the nature of substrate of Late Paleozoic granites in the South Urals," Litosfera, No. 3, 5–16 (2015).
57. G. B. Fershtater, *Paleozoic Intrusive Magmatism in the Middle and South Urals* (Ural. Otd. Ross. Akad. Nauk, Yekaterinburg, 2013) [in Russian].
58. V. V. Kholodnov, G. B. Fershtater, N. S. Borodina, G. Yu. Shardakova, S. V. Pribavkin, E. S. Shagalov, and T. D. Bocharnikova, "Granitoid magmatism in the junction zone between the Urals and East European Platform (Southern Urals)," Litosfera, No. 3, 3–28 (2006).
59. E. V. Chibrikova and V. A. Olli, "Once more on pre-Paleozoic deposits in the South Urals and in Cis-Uralian region," *Geology, Mineral Resources and Geoecological Problems of Bashkortostan: Proceedings of the 6th Interregional Research-and-Practice Conference, Ufa, Russia, 2006* (DizainPoligrafServis, Ufa, 2006), pp. 54–57.
60. G. Yu. Shardakova, E. S. Shagalov, and M. S. Sereda, "Geochemical distinctions of granitoids in the Taganai-Iremel Anticlinorium (Central Ural Megazone)," Dokl. Earth Sci. **413**, 424–427 (2007).
61. K. N. Shatagin, O. V. Astrakhantsev, K. E. Degtyarev, and M. V. Luchitskaya, "The heterogeneity of the continental crust in the Eastern Urals: The results of an isotope-geochemical study of Paleozoic granitoids," Geotectonics **34**, 380–396 (2000).
62. R. R. Yakupov, T. M. Mavrinskaya, and A. N. Abramova, *Paleontological Validation of the Paleozoic Stratigraphic Scheme for the Northern Part of the Zilair Megasynclinorium* (Inst. Geol. Geokhim. Ural. Otd. Ross. Akad. Nauk, Yekaterinburg, 2002) [in Russian].
63. S. V. Bogdanova, B. Bingen, R. Gorbatschev, T. N. Kheraskova, V. I. Kozlov, V. N. Puchkov, and Yu. A. Volozh, "The East European Craton (Baltica) before and during the assembly of Rodinia," Precambrian Res. **160**, 23–45 (2008).
64. U. A. Glasmacher, W. Bauer, U. Giese, P. Reynolds, B. Kober, V. Puchkov, L. Stroink, A. Alekseyev, and A. P. Willner, "The metamorphic complex of Beloretzk, SW Urals, Russia—a terrane with a polyphase Meso-to Neoproterozoic thermo-dynamic evolution," Precambrian Res. **110**, 185–213 (2001).
65. U. A. Glasmacher, P. Reynolds, A. A. Alekseyev, V. N. Puchkov, K. Taylor, V. Gorozhanin, and R. Walter, "^{40}Ar/^{39}Ar thermochronology west of the Main Uralian fault, Southern Urals, Russia," Geol. Rundsch. **87**, 515–525 (1999).
66. I. Görz, K. Bombach, U. Kroner, and K. S. Ivanov, "Protolith and deformation age of the Gneiss-Plate of Kartali in the southern East Uralian Zone," Int. J. Earth Sci. **93**, 475–486 (2004).
67. S. E. Jackson, N. J. Pearson, W. L. Griffin, and E. A. Belousova, "The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology," Chem. Geol. **211**, 47–69 (2004).
68. V. Kovach, K. Degtyarev, A. Tretyakov, A. Kotov, E. Tolmacheva, K. L. Wang, S. L. Chung, H. Y. Lee, and B. M. Jahn, "Sources and provenance of the Neoproterozoic placer deposits of the Northern Kazakhstan: Implication for continental growth of the western Central Asian Orogenic Belt," Gondwana Res. **47**, 28–43 (2017).
69. N. B. Kuznetsov, J. G. Meert, and T. V. Romanyuk, "Ages of detrital zircons (U/Pb, LA-ICP-MS) from the Latest Neoproterozoic–Middle Cambrian (?) Asha Group and Early Devonian Takaty Formation, the Southwestern Urals: A test of an Australia-Baltica connection within Rodinia," Precambrian Res. **244**, 288–305 (2014).
70. N. Kuznetsov, S. Orlov, and T. Romanyuk, "Composition, structure and age of the Kamsak migmatites, Southern Urals," Mineral. Spec. Pap. **38**, 56–57 (2011).
71. N. M. Levashova, M. L. Bazhenov, J. G. Meert, N. B. Kuznetsov, I. V. Golovanova, K. N. Danukalov, and N. M. Federova, "Baltica in the end-Ediacaran: New paleo-magnetic and geochronological data," Precambrian Res. **236**, 16–30 (2013).
72. *The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghanian-Variscan Collision*, Vol. 423 of *Geol. Soc. Am., Spec. Pap.*, Ed. by U. Linnemann, R. D. Nance, P. Kraft, and G. Zulauf (Geol. Soc. Am., Boulder, Colo., 2007).
73. S. Sindern, R. Hetzel, B. A. Schulte, U. Kramm, Yu. L. Ronkin, A. V. Maslov, and O. P. Lepikhina, "Proterozoic magmatic and tectonometamorphic evolution of the Taratash complex, Central Urals, Russia," Int. J. Earth Sci. **94**, 319–335 (2005).
74. Ch. J. Spencer, P. A. Cawood, Ch. J. Hawkesworth, A. R. Prave, N. M. W. Roberts, M. S. A. Horstwood, and M. J. Whitehouse, "Generation and preservation of continental crust in the Grenville Orogeny," Geosci. Frontiers **6**, 357–372 (2015).

Reviewers: V.N. Puchkov, T.N. Kheraskova

Translated by I. Melekestseva