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GEOLOGY

New Constraints for the Age of Vendian Glacial Deposits (Middle Urals)

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In the Earth's history, the first half of the Late Riphean and Vendian were marked by several significant biospheric (paleogeographic, geochemical, biotic) reorganizations that occurred against the background of discrete glacial episodes united into the so-called African Glacial Era [1]. In Europe, this glacial era is represented by glacial facies that are developed within the Serebryanka and Sylvitsa groups of the Middle Urals, the Glussk and Blon formations of the Orsha aulacogen in Belarus, the Port Askaig Formation in Scotland, and the Smallfjord and Mortensnes formations of Finnmarken in Norway (1). The new isotopic–geochronological data allow the entire Tanin–Starye Pechi glaciogenic succession of the Middle Urals to be considered as being younger as compared to the Marinoan glacial episode.

Among Upper Precambrian deposits developed on the western slope of the Middle Urals (Kvarkush–Kamennogorsk meganticlinorium), glacial facies are recorded with the Tanin and Koiva formations corresponding to the lower and middle parts of the Serebryanka Group and in the lower subformation of the Starye Pechi Formation that represents a basal unit of the Sylvitsa Group (Fig. 1) [1, 2]. The Tanin Formation up to 450–500 m thick is composed of massive diamictites separated by a member of sandstones and shales with dropstones. Its basal part includes basic volcanics, dolomites, dolomitized limestones, and shales; locally, sandstones, gravel, and slump breccias are observable. The Koiva Formation 250–600 m thick unites variegated clayey and silty–clayey shales, siltstones, variegated limestones, and dolomites; some sections in the northern part of the Kvarkush–Kamennogorsk meganticlinorium include packets and members of conglomerates with rare pebbles (mixtites) and pillow basalts (Shpalorez Hole and other areas). The Starye Pechi Formation up to 500 m thick is largely represented by yellowish–greenish gray thin-bedded siltstones and variegated thin-bedded mudstones. Its lower part encloses massive and bedded diamictites intercalated by subordinate shales with dropstones.

The diamictic texture, massive structure, and structural uniformity of diamictites over a significant region, their wide lateral distribution, and the occurrence of erratic rock fragments and dropstones are considered as representing their main diagnostic features [2]. At the same time, the last author notes that the number of such features is limited. The occurrence of sediments related to the shield glaciation (Churochnaya Formation) on the Polyudov Range provides grounds for the assumption that similar or close conditions existed also in the region under consideration [3]. According to these authors, diamictites of the Tanin, Koiva, and Starye Pechi formations may represent distal facies of shelf glaciers and products of iceberg rafting. They are also accompanied by members of inter- and postglacial dolomites, fan sediments of subice rivers, turbidites, submarine–colluvial, and slump facies. The Tanin–Starye Pechi glacial succession of the Middle Urals was estimated to be Early Vendian in age (corresponding to the Laplandian glacial horizon) [3]; in [3], the Vendian is considered as lasting from 600 to 590 Ma ago [3, Fig. 10].

Owing to recent investigations, the minimal age of this glacial succession is substantially specified based on data on the U–Pb isotopic composition of zircons from volcanic tuffs occurring in the Perevalok Formation of the Sylvitsa Group (567.2 ± 3.9 Ma [4]. In the mid-1990s, the Sm–Nd and Rb–Sr dates of 569 ± 42 and 559 ± 16 Ma, respectively, were obtained for trachyandesites of the Dvorets Complex localized among the sedimentary Kernos Formation. The Sm–Nd age

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Level of the composite section	Group	Formation	Levels with diamictites	Isotopic age (Ma). material, method
Upper Vendian	Sylvitsa	Ust'-Sylvitsa		
		Chernyi Kamen		557 ± 13 (Zircons, U–Pb SHRIMP, volcanic tuffs)
		Perevalok		567.2 ± 3.9 (Zircons, LA-ICP-MS, volcanic tuffs)
		Starye Pechi		561 ± 36 (Zircons, LA-ICP-MS, volcanic tuffs)
Lower Vendian			■	
	Serebryanka	Kernos		569 ± 42 (pyroxene monofraction and bulk rock, Sm–Nd, trachyandesites), 559 ± 16 (pyroxene monofraction and bulk rock, Rb–Sr, trachyandesites), 626 ± 57 (apatite and pyroxene monofraction and bulk rock, Sm–Nd, alkali gabbro)), 608 ± 3 (pyroxene monofraction and bulk rock, Rb–Sr, picrites)
		Buton		
		Koiva	■	
		Garevo		
		Tanin	■	598.1 ± 6.0 (zircons, LA-ICP-MS, alkali basalts)
Upper Riphean	Baseg	Shchegrovit		672 ± 22 (bulk rock, Rb–Sr method, trachyandesites)

Fig. 1. Composite stratigraphic column of the Serebryanka and Sylvitsa groups developed on the western slope of the Middle Urals and the isotopic age of their lithostratigraphic units (recent data)

of alkali gabbro from the Kus'ya Complex, which constitutes along with the Dvorets Complex a single volcano-plutonic association, is estimated to be 626 ± 57 Ma, while picrites are dated by the Rb–Sr method back to 608 ± 3 Ma [5, 6]. The subsequent Sm–Nd dating of rocks from the Dvorets Complex yielded the age estimate of 561 Ma with significant uncertainty (±300 Ma, MSWD = 7.1) [7]. It seems that volcanics of the Dvorets Complex reflect migration of magmas from chambers of various depths along a common permeable structure, which was accompanied by contamination of different substrates, rather than represent differentiation and crystallization products of magma from a single chamber. As is shown below, such a property is also characteristic of basalts from the basal part of the Tanin Formation.

The maximal age for glacial deposits from the Middle Urals was determined until recently by dates obtained for volcanics from the Shchegrovit trachybasalt–trachyte complex that occurs among sedimentary rocks constituting the upper part of the Upper Riphean Base Group (672 ± 22 Ma, Rb–Sr method) [6] and their hypabyssal analogs represented by quartz alkali syenties of the Troitsk massif (671 ± 24 Ma, U–Pb method on zircons) [8]. These dates provided grounds for the cautious assumption that the Tanin and Koiva formations may belong to the lower Laplandian glacial horizon and the lower formation of the Starye Pechi Formation to its upper part [1, 9]; i.e., they correspond to the Marinoan and Gaskier glacial episodes, respectively.

In 2002–2003, Grazhdankin [10] recorded volcanic tuff beds in the upper part of the Starye Pechi Formation in the Sylvitsa River basin and northern pericline of the Vilukha anticline in the Us'va River basin (58°47.401′ N, 57°59.248′ E, Sample SP-1) (Figs. 2, 3a). Zircons from this sample (83 grains) were dated by the LA ICP-MS U–Pb method at the University of Florida (United States) on the New-Wave 213 nm equipment integrated with the sector multichannel NU Instruments mass spectrometer. (The technical parameters of the equipment, standards, and other characteristics of the U–Pb zircon dating method are available from the site http://web.geology.ufl.edu/Isotope/icp-ms.html). The LA ICP-MS U–Pb data on 83 zircon grains are characterized by a relatively small discordance (from –9 to +9) and their discrete–continuous succession in the ^{207}Pb/^{235}U–^{206}Pb/^{235}U plot. The oldest concordant age of zircons (2867 ± 13 Ma, MSWD = 1.8) is determined by two data points. In the same fragment of the concordia, another area is represented by 17 data points (^{207}Pb/^{235}U ages range from 2740 to 2376 Ma); their ellipses of 2σ errors practically overlapped in this interval reflecting probable likely loss of radiogenic lead. Similar patterns with practically continuous overlapping of 2σ error ellipses, although in a wider age interval (^{207}Pb/^{206}Pb ages range from 2175 to 966 Ma), are also observed for the LA ICP-MS U–Pb data represented by the remaining 62 data points. Zircons (ellipses 1/59, 1/60; Fig. 3b) yielded a minimal age of 561 ± 36 Ma (confidence level of 95% without regard for the decay constant error). A similar age value is also derived from the algorithm of ISOPLOT/EX 3.65 version (K. Ludwig, 2012). The above-mentioned date with account for the mineralogical properties of zircons determined by optical and cathode–luminescence observations (CL, BSE) may be considered as the best among age estimates obtained for the upper part of the Starye Pechi

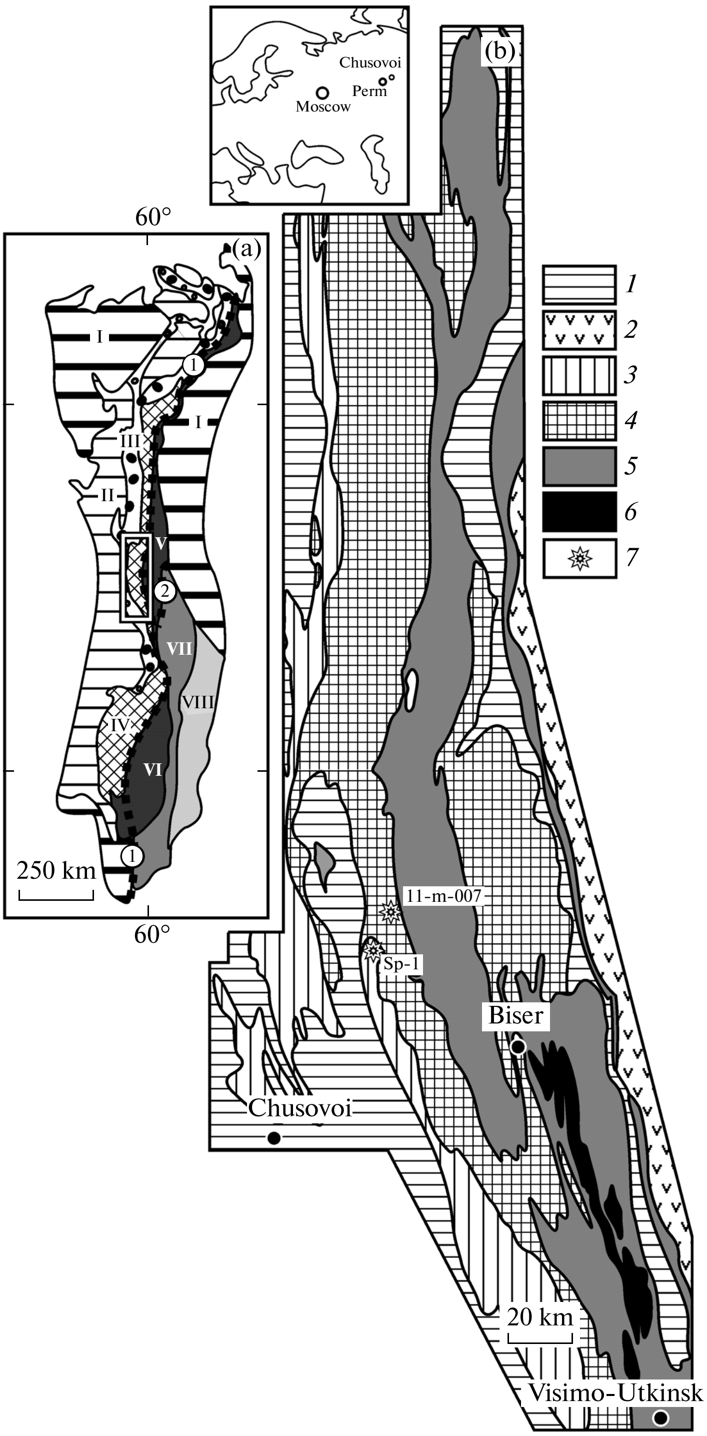

Fig. 2. Survey map of the Urals (a) and schematic geological map of the Kvarkush–Kamennogorsk meganticlinorium (b) with sampling sites for isotopic dating. (I) Mesozoic–Cenozoic rocks; (II) Uralian foredeep; (III–VIII) megazones of the Urals: (II) West Urals, (IV) Central Urals, (V) Tagil, (VI) Magnitogorsk, (VIII) East Urals, (VIII) Transurals. Encircled numbers: (1) Main Uralian fault, (2) Serov–Mauk fault. Rectangle designates the Kvarkush–Kamennogorsk meganticlinorium. (*1, 2*) Paleozoic: (*1*) Central Uralian megazone, (*2*) Tagil megazone; (*3, 4*) Vendian: (*3*) Sylvitsa Group, (*4*) Serebryanka Group; (*5, 6*) Upper Riphean: (*5*) Baseg Group, (*6*) Kedrovo Group; (*7*) sampling sites.

Formation (consistent with available data on ages of the Chernyi Kamen and Perevalok formations; Fig. 1).

In 2011, several samples (11-m-005, 11-m-006, 11-m-007) of alkali basalts were taken from pillow-lava flows occurring in the lower part of the Tanin Formation on the right bank of the Us'va River 6 km west of the Kompasechnyi Creek mouth and 2.5 km north of the Bol'shoe Poboishche Creek (58°59.435′ N,

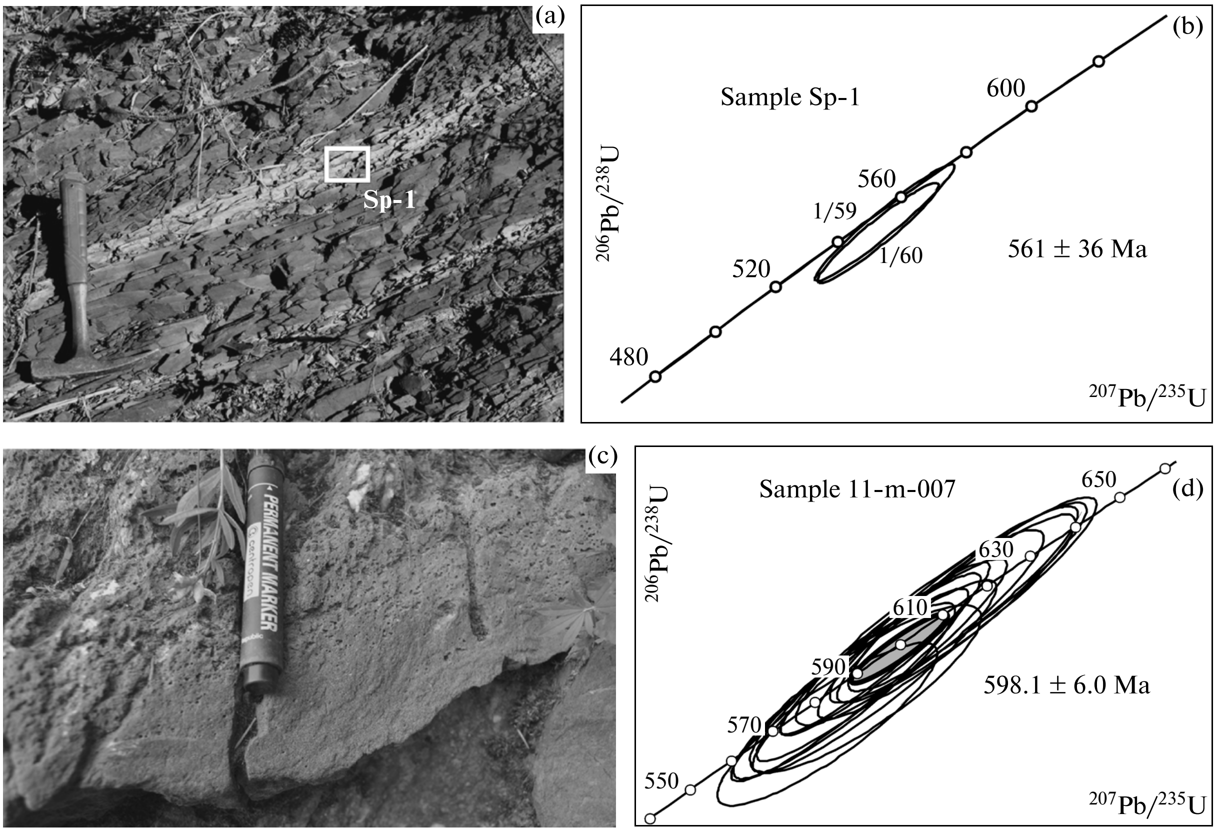

Fig. 3. Volcanic ashes from the upper part of the Starye Pechi Formation in the Vilukha Hole on the left side of the Us'va River (Sample SP-1) (a, photo by A.V. Maslov), pillow basalts from the basal part of the Tanin Formation, Sample 11-m-007 (c, photo by N.M. Fedorova), and fragments of the Arens–Wetherill plots for extracted zircons (b, d).

58°17.972′ E) (Figs. 2, 3a). The most representative zircon population (76 grains) extracted from Sample 11-m-007 was also dated at the University of Florida. The LA ICP-MS U–Pb data for zircons from this sample indicate the significant age scatter (from the Archean to Vendian) exhibiting discordance ranging from –15 to +49. The "oldest" U–Pb concordant age is 3441 ± 25 Ma (± 2σ; n = 1). Younger U–Pb ages obtained for zircons are equal to 2770 ± 31 Ma (n = 2) and 2448 ± 360 Ma (n = 2). The next fragment of the Arens-Wetherill plot exhibits several clusters with ages ranging from 1923 ± 30 Ma (n = 4, 95% confidence level) to 1260 ± 26 Ma (n = 3, ± 2σ). The cluster uniting nine data points yields the calculated concordant age of 810 Ma (MSWD = 0.28, probability of concordance consistency 0.6). The population represented by 45 data points may be divided into two groups based on different discordances. The first group (n = 32) is characterized by a significant discordance (up to 49%). The second group uniting 13 data points corresponds to the concordant cluster with the age of 598.1 ± 6.0 Ma (± 2σ without regard for the decay constant error, MSWD = 1.3) (Fig. 3d). Taking into consideration the mineralogical properties of the examined zircons derived from optical and cathode luminescence observations (CL, BSE), we consider this age as the most reliable one for pillow-basalt flows alternating with terrigenous rocks at the base of the Tanin Formation in the upper reaches of the Us'va River. (It is of interest that subsidence-related catagenesis of authigenic illite contained in clayey rocks from diamictites of the Tolparovo Formation developed on the western slope of the South Urals traditionally correlated with the Tanin Formation of the Kvarkush–Kamennogorsk meganticlinorium [11] is dated by the Rb–Sr method at 593 ± 15 Ma [12]).

According to recent views [13 and references therein], the Neoproterozoic (1000–541 Ma) comprises three distinct glacial episodes: Sturtian, Marinoan, and Gaskier. Glacial deposits of the Sturtian episode are usually associated with dark-colored C_{org}-rich cap carbonates and Fe-enriched sedimentary rocks. The most likely maximal age limit for the episode in question is determined by a date of 746 ± 2 Ma obtained for the Naauwpoort volcanics underlying the glaciogenic Chuos Formation on the Congo Craton. The glaciogenic Ghubrah Formation in Oman is as old as ~712 Ma. The Areyonga Formation in the Amadeus basin of Australia correlated with typical Sturtian glacial rocks is overlain by black shales of the Aralka Formation dated by the Re–Os method back to 657.2 ± 5.4 Ma; this date is considered as rep-

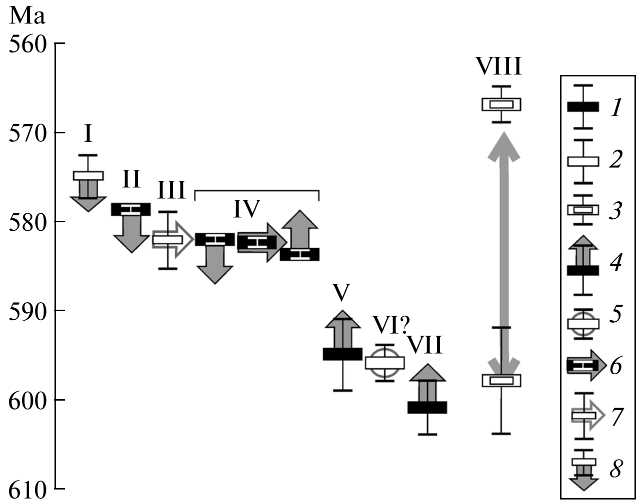

Fig. 4. U–Pb isotopic (zircon) age constraints for Ediacaran glaciations, after [14] slightly modified and age constraints for the Vendian glacial succession developed on the western slope of the Middle Urals. (I) Grimes Intrusive Suite, Grassy Group, Tasmania; (2) Drook Formation, Conception Group, Newfoundland; (III) Croles Hill Formation, Kanunnah Subgroup, Tasmania; (IV) Gaskiers Formation, Conception Group, Newfoundland; (V) Tayvallich Formation, Dalradian Subgroup, Scotland; (VI) Squantum Formation, Boston Bay Group, eastern United States; (VII) Tayvallich Formation, Dalradian Subgroup, Scotland; (VIII) Serebryanka and Sylvitsa groups, Middle Urals, (*1*) ID-TIMS U–Pb zircon age (uncertainty ±2σ; (*2*) SHRIMP U–Pb zircon age (uncertainty ±2σ; (*3*) LA ICP-MS U–Pb zircon age (uncertainty ±2σ; (*4*) maximal age limit for glacial sediments; (*5*) age of detrital zircons from glacial sediments; (*6*) syn-sedimentation age obtained for glacial sediments; (*7*) syn-sedimentation age obtained for diamictites of uncertain genesis; (*8*) minimal age limit for glacial sediments.

resenting the minimal age of the Sturtian glacial episode. The U–Pb age of the Datangpo Formation in China resting immediately upon the glaciogenic Tiesiao Formation is 663 ± 4 Ma. All these data provide grounds for the conclusion that the age limits for Sturtian glacial deposits correspond to ~746–663 Ma [13].

The maximal age of glacial sequences deposited during the Marinoan episode is recorded in China and Australia. In China, the top of the preglacial Datangpo Formation is dated by the U–Pb method at 654 ± 3.8 Ma. The isochron Re–Os age of the Tindelpina black shale member underlying the glaciogenic Tapley Hill Formation in Australia is as old as 643 ± 2.4 Ma. Zircons from volcanic tuffs of the Ghaub Formation in Oman yielded an age of 635.5 ± 1.2 Ma. A similar age (636.3 ± 4.9 Ma) was obtained for the lower part of the glacial Nantuo Formation in China, while volcanic ashes from overlying cap carbonates were dated back to 635.2 ± 0.6 Ma. These and some other data indicate that the age limits for the Marinoan glacial episode correspond to ~650–635 Ma [13].

The younger (Ediacaran) glacial successions are documented on at least three paleocontinents [13]. Among these successions, the Gaskier Formation in Newfoundland of Canada is the best known. The period of its deposition lasted slightly less than 3 Ma (Fig. 4). Coeval glacial successions are also recorded in the northeastern margin of Laurentia, in Baltia, and the Tarim block of China, although their ages are still ambiguous, which makes assumptions on synchronism of post-Marinoan glaciation(s) highly speculative.

When our data obtained for the Middle Urals are compared with the above-cited age constraints available for different Neoproterozoic glacial episodes, the fact that the entire Tanin–Starye Pechi succession belongs to the youngest Ediacaran (post-Marinoan) interval becomes obvious, although the age limits for the Middle Urals glacial succession are more than an order of magnitude wider as compared with the duration of the Gaskier glacial episode proper. It is conceivable that the obtained original data will allow in the future age constraints for the Laplandian glacial horizon to be specified as well. At the same time, taking into consideration that some diamictite sequences attributed to this interval (for example, the Squantum Tillites in the Boston basin) are recently interpreted as deepwater gravitational sediments [15], the search for additional unambiguous criteria for the glacial or glaciomarine origin of diamictites in the Middle Urals seems to be topical.

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