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GEOLOGY

Late Vendian Miaohe-type Ecological Assemblage of the East European Platform

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Upper Vendian rocks of the East European Platform (EEP) are characterized by the presence of the White Sea fossil biota, which colonized the region from the southeastern White Sea area to the Central Urals [1]. The White Sea biota includes ecological assemblages of the Avalon (Newfoundland), Ediacara (South Australia), and Nama (Namibia) types, each related to certain environmental conditions [2]. In 2006, we found a previously unknown and morphologically diverse assemblage of carbonaceous macroscopic fossils in the fine-grained aluminosiliciclastic rocks of the Perevalok Formation (Sylvitsa Group) in the Central Urals. Together with the organic-walled macrofossils from the rocks of the Lyamtsa Formation (Valdai Group) in the southeastern White Sea area, the carbonaceous fossils from the Perevalok Formation represent a new (fourth) ecological assemblage of the White Sea fossil biota. The ecological assemblage is older than 557–558 Ma [3, 4] and includes macroscopic microbial colonies, multicellular and coenocytic eukaryotic macroalgae. In the Late Vendian history of the EEP, this assemblage predated the appearance of the world's most diverse soft-bodied assemblage, which was found in the overlying rocks of the White Sea area (Verkhovka and Erga formations) and Central Urals (Chernokamen Formation) [1, 2, 5].

The carbonaceous fossils are confined to a thick (200–400 m) transgressive sequence at the base of the Upper Vendian succession in the southeastern White Sea area and Central Urals (Fig. 1). The lower part of the sequence (laminated mudstones with layers of volcanic tuffs) is gradually replaced upsection by thinly interbedded siltstones and mudstones with rare layers of wave-bedded sandstones. The sequence was formed by the advance and periodic retreat of storm-dominated coastal depositional setting into subaqueous muddy planes with relatively quiet sedimentation in the course of oscillating wane in transgression. Fossiliferous intervals contain thin laminae of phosphorites and organic matter and mark the peak of shallow-water transgression over the platform. In the southeastern White Sea area, this sequence correlates with the Lyamtsa Formation and lower part of the Verkhovka Formation; in the Central Urals, with the upper part of the Staropechny and Perevalok formations [6, 7] (Fig. 1).

In the southeastern White Sea area, a diverse assemblage of organic-walled macrofossils of the Lyamtsa Formation was found in the core from borehole C18 (depth 214–54 m), which was drilled in 1996 on the right bank of the Agma River Valley, Onega Peninsula [3]. The assemblage is dominated by compressed spherical chuariamorph fossils of Beltanelloides sorichevae Sokolov, but special attention should be given to the fragments of geniculated compressed hollow tubes (up to 80 mm long and 9 mm wide) of Sinospongia chenjunyuani Chen with thin regular transverse wrinkles (Figs. 2d, 2f). In view of the small core size, the tube ends were not observed. In some places, collapsed organic matter is preserved along the tube axis as a dark brown carbonaceous ribbon with impressions of transverse wrinkles (Fig. 2e). The organic matter of the tubes is thin, yellow, and structureless. In addition to Sinospongia, the Lyamtsa Formation contains relatively narrow (1–1.35 mm wide) curved compressed tubes of Jiuqunaoella simplicis Chen (Fig. 2g) with thin light yellow walls and thin transverse wrinkles. Their content is collapsed into chains of brown ovoid spots of organic matter with fold impressions (Fig. 2h). The Lyamtsa assemblage also includes narrow (0.85–1 mm) relatively thick-walled dark brown sinusoid compressed tubes with thin transverse wrinkles (Fig. 2i). In addition to tubular fossils, optically dense wide (up to 6 mm) ribbon of Mezenia kossovoyi Sokolov was found in the mudstones of the Lyamtsa Formation. Its smooth surface was distorted during burial by weak transverse undulation, sharp longitudinal and arched

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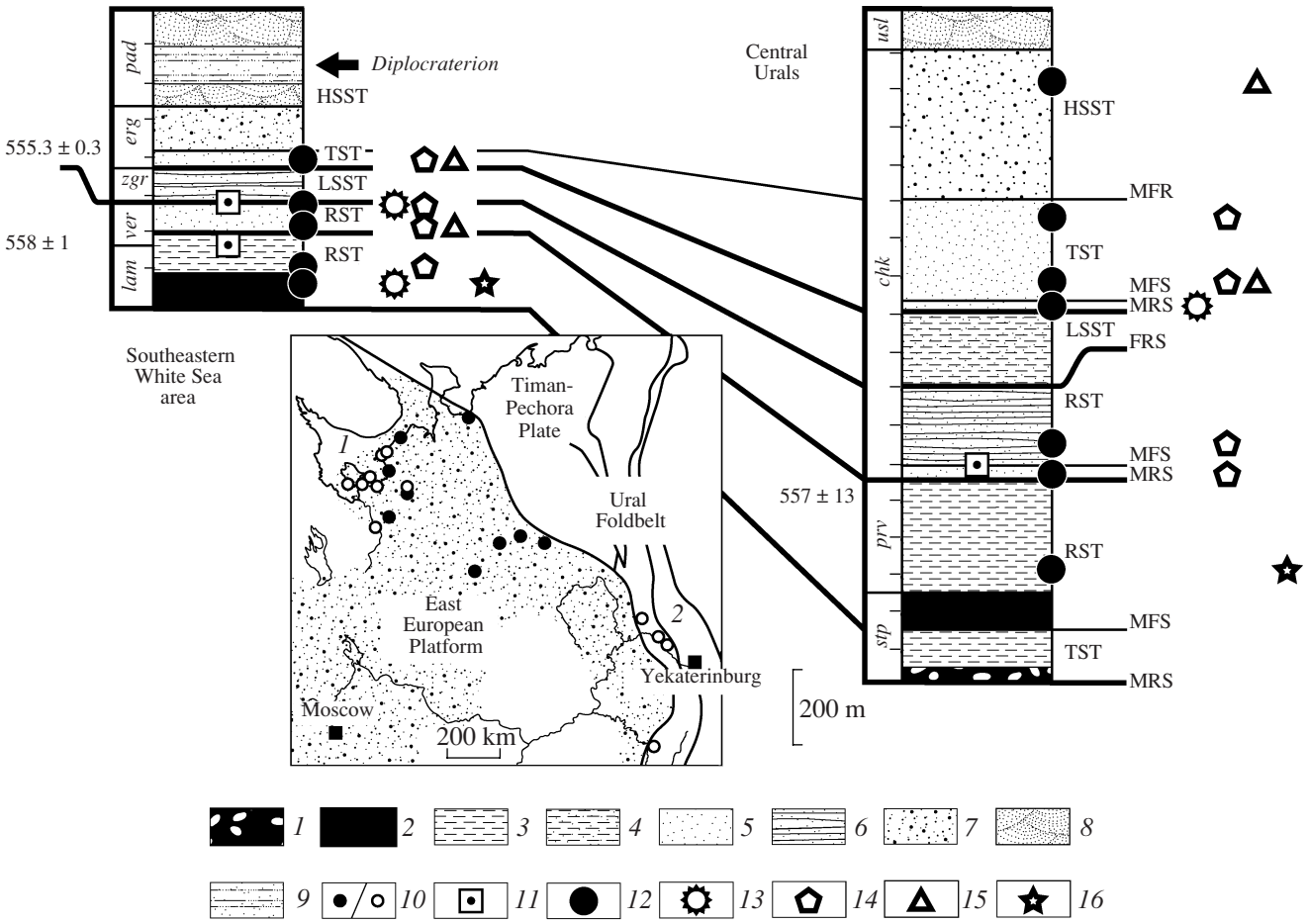

Fig. 1. Sequence–stratigraphic framework of Upper Vendian rocks of the northeastern East European Platform and Urals and distribution of ecological assemblages of the White Sea fossil biota (trace fossils Diplocraterion in the section of the southeastern White Sea area indicate a Lower Cambrian age of rocks of the Padun Formation). The map shows the distribution of the Upper Vendian rocks and localities with fossils of the White Sea fossil biota. (*1–9*) Facies: (*1*) diamictites, (*2*) laminated mudstones, (*3*) interbedded siltstones and mudstones, (*4*) interbedded siltstones and sandstones; (*5*) wave-bedded sandstones, (*6*) alternating sandstones, (*7*) sandstones with multistory cross-bedding, (*8*) sandstones with trough cross-bedding, (*9*) sandstones with flaser bedding; (*10*) boreholes/exposures, (*11*) stratigraphic position of volcanic tuffs dated by the U–Pb zircon method; (*12*) stratigraphic position of fossiliferous levels; (*13–16*) fossil ecological assemblages: (*13*) Avalon; (*14*) Ediacara, (*15*) Nama, (*16*) Miaohe. Formations: (lam) Lyamtsa, (ver) Verkhovka, (zgr) Zimnegory, (erg) Erga, (pad) Padun, (stp) Staropechny, (prv) Perevalok, (chk) Chernokamen, (usl) Ust-Sylvitsa; (TST) transgressive systems tract, (RST) regressive systems tract, (LSST) lowstand systems tract; (HSST) highstand systems tract; (MRS) marine regression surface; (MFS) marine flooding surface, (FRS) forced regression surface.

folds, and thin longitudinal wrinkles (Figs. 2a–2c). The carbonaceous fossils of the Lyamtsa Formation also include phytoleims of the macroscopic algae Archyfasma dimera Gnilovskaya, which were found in the core from borehole 776 Ilos drilled in the White Sea–Kuloi plateau in the 1980s.

In the Central Urals, the assemblage of more diverse (in terms of taxonomy, frequency of occurrence, and abundance) carbonaceous macrofossils characterizes rocks of the Perevalok Formation exposed in the bank escarpment of Krutaya Gora in the middle reaches of the Us'va River. The oryctocenosis includes at least ten varieties: large disk-shaped concentric Cyclomedusa davidi Sprigg (Fig. 3e), compressed helicoidal-cylindrical Grypania spiralis (Walcott) (Fig. 2d), compressed ellipsoidal Tawuia dalensis Hofmann (Fig. 3j), straight narrow (1–3 mm) ribbons (Fig. 3h), wide (up to 20 mm or more) ribbon-shaped fossils with transverse structure (Fig. 3b), fragments of zoned bodies (Fig. 3g), wide ribbon-shaped elliptical and lanceolate fossils (Fig. 3c), filaments Liulingjitaenia alloplecta Chen et Xiao with helically arranged longitudinal plicate folds (Fig. 3f), smooth ribbons of Mezenia kossovoyi (Fig. 3i), and clusters of hook-shaped filaments (Fig. 3a).

The assemblage of carbonaceous fossils in the rocks of the Lyamtsa and Perevalok formations is interpreted as fossil communities of macroscopic (more than 1 mm), multicellular, and coenocytic eukaryotic algae. It is impossible to systematize these fossils reliably, because classification of modern algae is based on biochemical and cytological data, while morphological characters of the thallus are subjected to convergence.

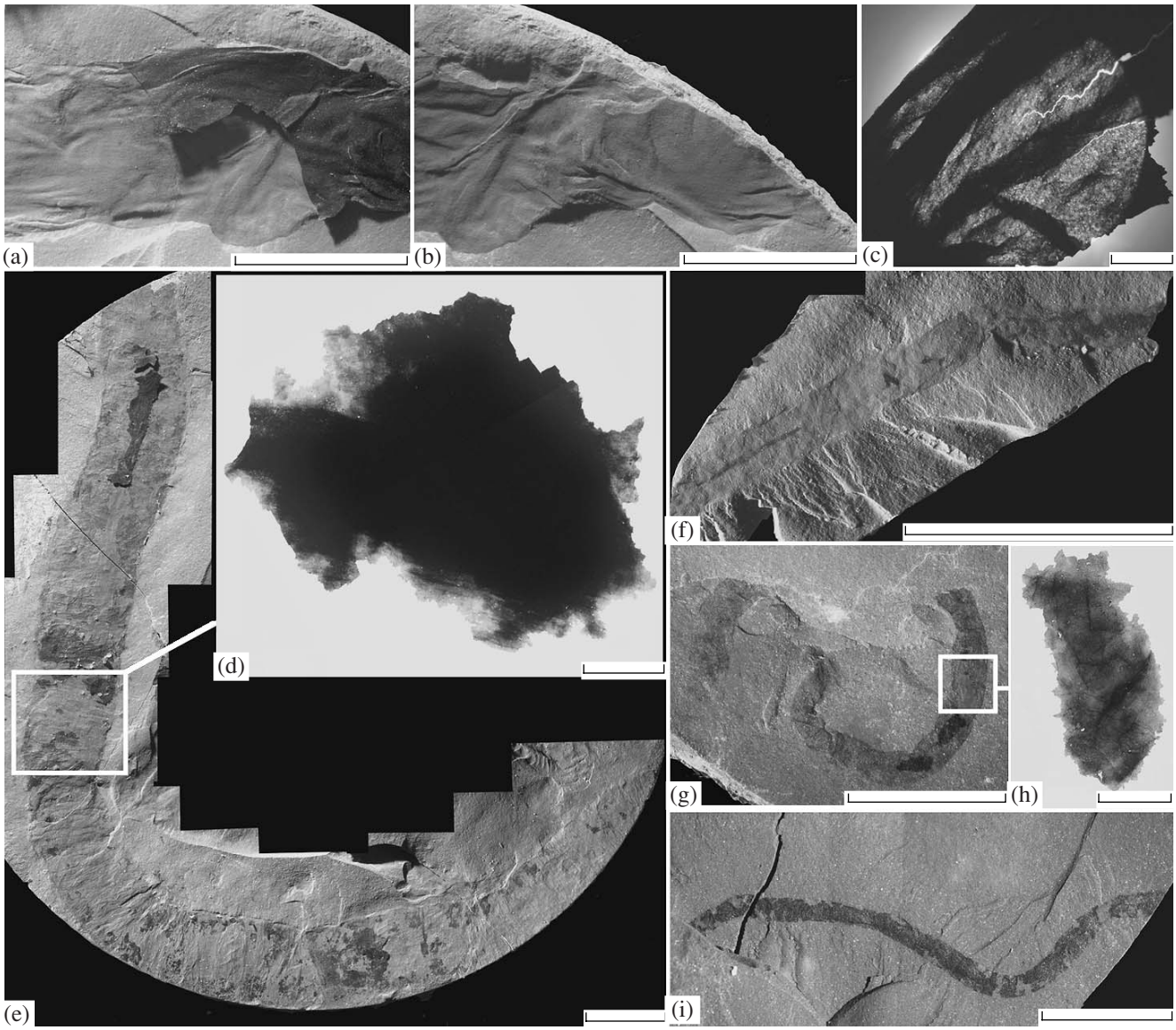

Fig. 2. Miaohe-type fossil assemblage of the Lyamtsa Formation, southeastern White Sea area: (a–c) Mezenia kossovoyi Sokolov; (d–f) Sinospongia chenjunyuani Chen, (g–h) Jiuqunaoella simplicis Chen, (i) narrow relatively thick-walled sinusoid compressed tubes with transverse wrinkles. Scale bar: (a, b, d, f, g, i) 5 mm, (c, e, h) 1 mm. Collection of the Institute of Petroleum Geology and Geophysics, Siberian Division, Russian Academy of Sciences. Photographs by A.A. Bronnikov.

Despite the similarity with sabelliditids, the compressed wrinkled tubes were interpreted as remains of siphonous algae [8, 9].

The Late Vendian is known as the epoch of morphological and ecological innovations in benthic algal communities. This was primarily manifested in the appearance of diverse forms with monopodial and spiral branching, forms with dichotomous branching and apical meristematic growth, and forms with lanceolate thallus and rhizoid holdfast organs [9]. In addition, the late Vendian was marked by the appearance and diversification of vendotaenid flora [10]. Until recently, the Doushantuo Formation (and coeval stratons) of South China containing diverse fossil microalgal assemblages of the Miaohe biota [8, 11, 12] was the main source of information on algal biota. Isotope–geochronological data define the age of the Miaohe biota as 551.1 ± 0.7 Ma [13]. Although scarce finds of Miaohe biota in the older rocks suggest an earlier diversification of macroalgae [14], the incompleteness of the fossil record significantly decreases the accuracy of paleobiological and evolutionary reconstructions. The discovery of diverse algal microbiota in the Upper Vendian of the EEP made it possible to fill this gap for the first time and to draw important conclusions on early stages of the evolution of macrophytes.

First, the assemblage of carbonaceous fossils of the EEP contains fossils of the Miaohe fossil biota of South

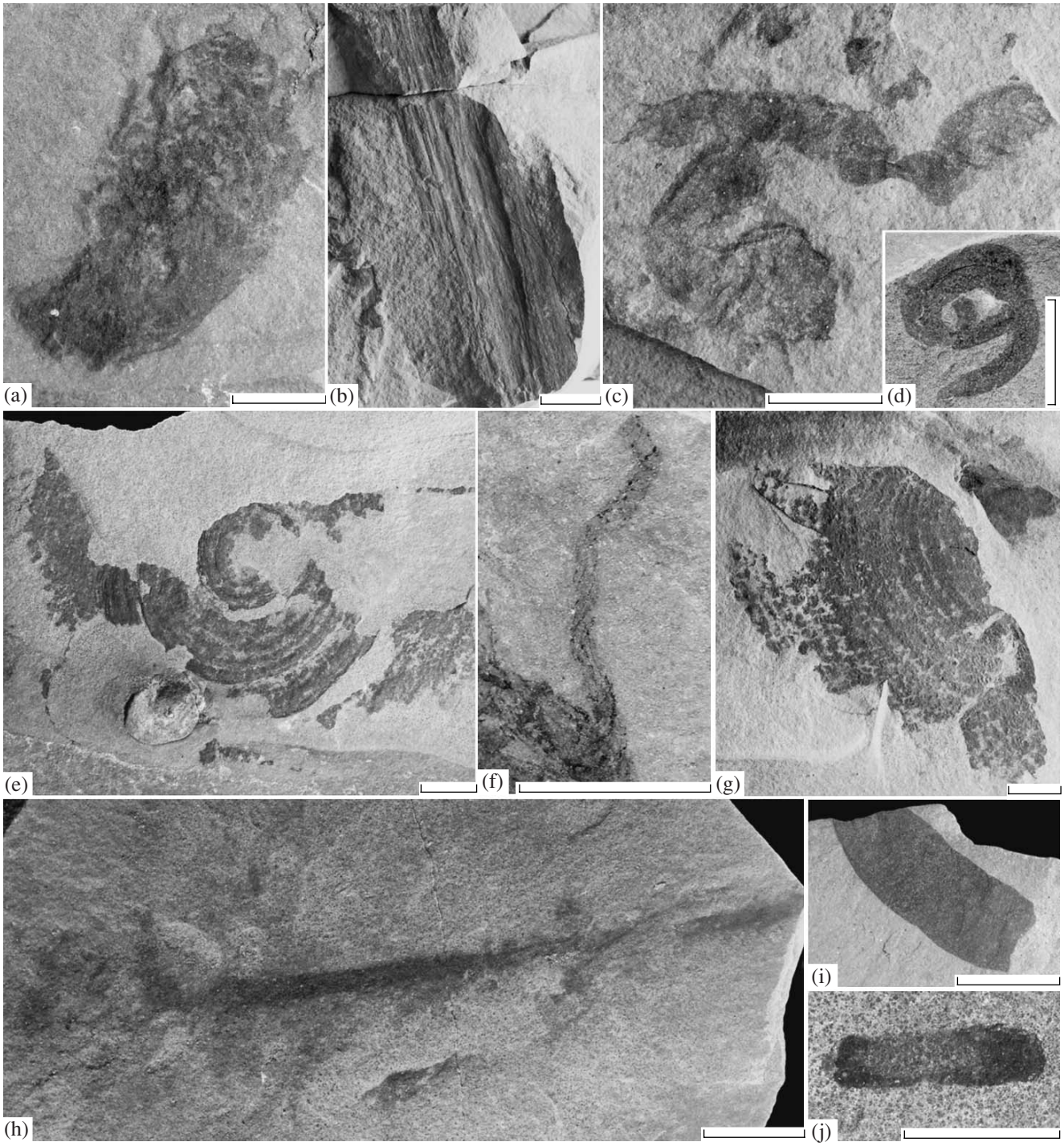

Fig. 3. Miaohe-type fossil assemblage of the Perevalok Formation of the Central Urals. (a) Cluster of hook-shaped filaments; (b) wide ribbons with transverse structure; (c) elliptical and lanceolate ribbons; (d) Grypania spiralis (Walcott); (e) Cyclomedusa davidi Sprigg; (f) Liulingjitaenia allopecta Chen et Xiao; (g) fragment of body with zoned structure; (h) straight narrow ribbon; (i) Mezenia kossovoyi Sokolov; (j) Tawuia dalensis Hofmann. Scale bar 10 mm. Collection of the Institute of Petroleum Geology and Geophysics, Siberian Division, Russian Academy of Sciences. Photographs by A.A. Bronnikov.

China: Sinospongia chenjunyuaini, Jiuqunaoella simplicis, and Liulingjitaenia alloplecta, whereas the Miaohe biota contains Beltanelloides sorichevae, Calyptrina striata Sokolov, and Cucullus fraudulentus Steiner (=Vaveliksia vana Serezhnikova) that are typical of Upper Vendian rocks of the EEP. In addition, rocks of the Perevalok Formation contain Tawuia dalensis and Grypania spiralis inherited from the older rocks. Tawuia was also found in the Miaohe biota. Grypania, a widespread alga in the pre-Riphean assem-

blage [9, 15], was found for the first time in the Vendian rocks. Although Upper Vendian rocks of the EEP lack the diverse branching forms that are typical of the Miaohe biota, the carbonaceous fossils of the White Sea area and Central Urals can be considered as a variety of the Miaohe ecological assemblage.

The Miaohe ecological assemblage of the EEP is older than that of South China. In the White Sea area, the Miaohe assemblage is located stratigraphically lower than the volcanic tuffs with a U–Pb zircon age of 558 ± 1 Ma [2, 3]. In the Central Urals, the fossiliferous sequence of the Perevalok Formation overlies the Chernokamen rocks with volcanic tuffs at the base dated by the U–Pb zircon method at 557 ± 13 Ma [4] (Fig. 1). The taxonomic and taphonomic similarity of the carbonaceous fossils from the White Sea area and Central Urals with the Miaohe assemblage of South China indicates not only a significant and earlier diversification of macroalgal communities, but also their differentiation at the earliest evolution stages.

Second, the benthic communities of the macroscopic alga in the photic zone of the continental shelf play an important role in modern marine ecosystems. They form dense underwater forests and turfs, the bioproductivity rate of which is higher than that of phytoplankton. They also act as "engineers" of new ecological niches, providing a substrate for nutrition, reproduction, and settlement for Metazoa. Therefore, the diverse macroalgal assemblage of the White Sea biota reported in this communication provides new insights into the structure and mechanism of functioning of Late Proterozoic ecosystems. In Upper Vendian rocks of the southeastern White Sea and Central Ural areas, the Miaohe ecological assemblage is related to the transgressive shelf sedimentary systems with low rates of clastic sediment supply and wave reworking. Together with the Avalon, Ediacara, and Nama ecological assemblages, the Miaohe assemblage is a full member of the White Sea biota. These assemblages coexisted in different depositional settings within a single basin. The presence of the Miaohe ecological assemblage in the EEP also indicates that the colonization and stabilization of sediment in the Late Proterozoic was controlled not only by microbial mats, but also by multicellular eukaryotes. Of special interest in this context is study of the gradual ecological replacement of microbial mats by macroalgae and the consequent reduction of the biotope favored by the Ediacara ecological assemblage.

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