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Structure and Depositional Environment of the Vendian Complex in the Southeastern White Sea Area

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Abstract—The subdivision and correlation scheme of the Vendian Complex is revised based on new data from outcrops along the eastern margin of the Baltic Shield (the southeastern White Sea area) and recently drilled boreholes. According to the established cyclic architecture of the sequence, the Vendian Complex is divided into the Lyamtsa, Verkhovka, Zimnie Gory, and Erga formations. Principal lithologic units of these subdivisions are described, and their facies relations and depositional environment are considered. It is suggested that the Vendian Complex accumulated in offshore settings as a result of southwestern progradation of a deltaic depositional system.

Key words: Vendian, stratigraphy, depositional environment, southeastern White Sea area.

INTRODUCTION

The Ediacara-type fossil biota of the southeastern White Sea area is the most informative one because of its high taxonomic diversity and extraordinary preservation (Fedonkin, 1981, 1990; Ivantsov, 1999, 2001; Grazhdankin, 2000). The Vendian Complex hosting these fossils is composed of sandy to clayey deposits exposed in relatively small and isolated outcrops each characterizing a part of the whole succession that is variably subdivided by different researchers. Moreover, the deposits have never been described in necessary details, which would properly characterize their depositional environment and settings and enable a correct understanding of stratigraphic and facies-controlled distribution of fossils in the sections. As a result, the insufficient data on habitat and burial conditions of organisms represent a serious impediment, when one is going to seek for new localities of organic remains.

The Vendian Complex of the southeastern White Sea area is up to 550 m thick and rests almost horizontally (the average dip angle not more than 0.2°) on the platform crystalline basement and Upper Riphean sediments filling the grabens and deep troughs in the latter (Stankovsky *et al.*, 1972, 1983; Yakobson *et al.*, 1991). Along the Baltic Shield eastern margin, Vendian deposits are exposed in river valleys crosscutting the Onega Ridge (Lyamtsa and Purnema rivers), a western part of the Dvina glint (Nizhma, Agma, Syuzma, Verkhovka, Solza, and Kinzhuga rivers), and the western White Sea-Kuloi glint (Torozhma and Zolotitsa rivers). In addition, they crop out along the Onega, Letnii, and Zimnii coasts of the White Sea. Toward the northeast, east, and southeast, Vendian strata plunge deeply under Paleozoic deposits of the Mezen syneclise.

The main objective of this work is to describe lithology of the Vendian Complex of the southeastern White Sea area, to revise the local scheme of its subdivision and correlation, and to interpret the depositional environment of corresponding sediments. The study is based on the bed-by-bed description of more than 150 outcrops in the Onega Peninsula and Kuloi Plateau and on investigation results of core samples from four boreholes drilled in the Onega Peninsula by the Syuzma Party of AO "Arkhgeoldobycha" in 1993 to 1996. In addition, the reference borehole sections described by E.A. Kalberg, A.I. Lebedintsev, and A.F. Stankovsky have been reexamined.

INVESTIGATION HISTORY

Deposits of the southeastern White Sea area, which are attributed now to the Vendian Complex, were comprehensively studied before the World War II by Kalberg who established in 1936–1937 that they bear organic remains originally identified as plant impressions and worm trails (the report of 1940 by Kalberg and Ershova). At that time, the clayey-sandy sequence bearing these remains and exposed in river valleys and in coastal cliffs of the White Sea was attributed to the Upper Devonian (Zekkel', 1939; Kalberg, 1940). In the period of 1947 to 1949, the Northern Geological Service drilled the boreholes Nenoksa, Arkhangelsk, and Ust-Pinega, which penetrated through the sedimentary cover of the region down to the crystalline basement. In 1950, Kalberg compared her field observations with data on these boreholes and subdivided the sequence into the Lyamtsa, Arkhangelsk, Verkhovka, Zimnie Gory, and Yagry formations (Fig. 1) based on predomi-

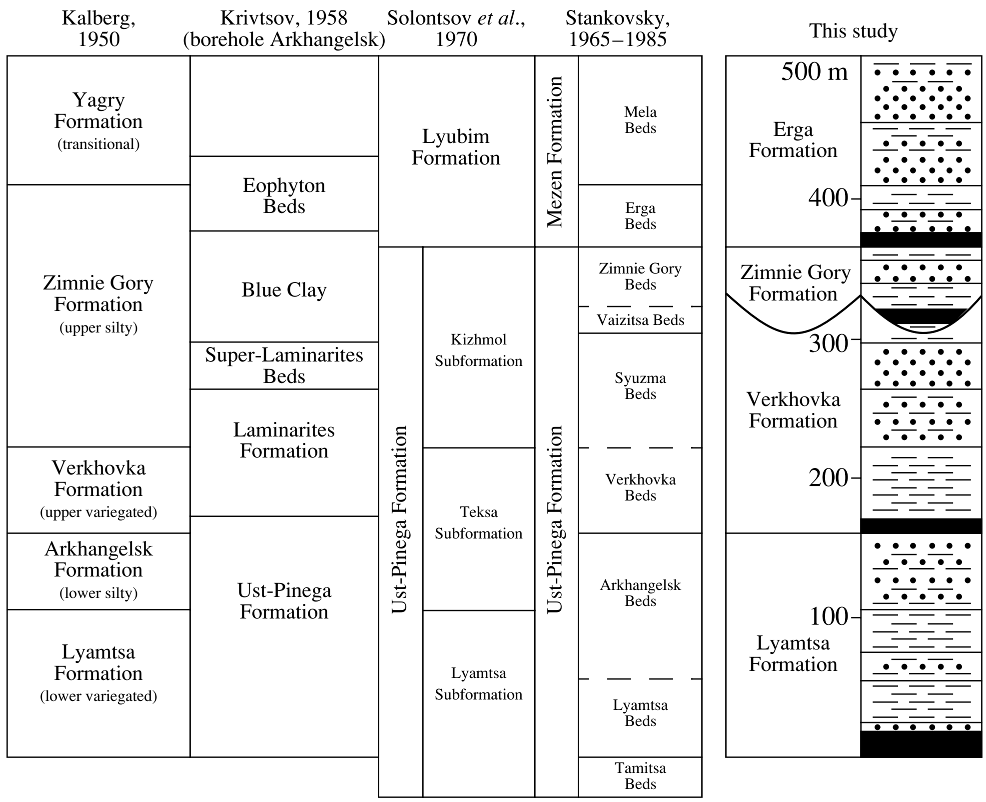


Fig. 1. Comparison of stratigraphic schemes suggested for Vendian deposits in the southeastern White Sea area (symbols as in Fig. 2).

nant coloration and petrographic composition of their rocks.

After the World War II, data of deep drilling in the East European platform showed that age of the oldest deposits in sedimentary cover must be revised, and in the northwestern and western platform areas there were distinguished the Vendian Complex of the terminal Precambrian and the overlying Baltic Group of the Lower Cambrian (Sokolov, 1952). In the 1950s, this stimulated reexamination of oldest deposits in the southeastern White Sea area, where they were found to bear remains of organic-walled tubular fossils resembling *Sabellidites cambriensis* Yanichevsky from Lower Cambrian deposits (Igolkina, 1956, 1959; Zoricheva, 1963). As a result, sedimentary strata with these remains were included into the Baltic Group, while the other ones the lacking fossils were attributed by Krivtsov (1958) to the Ust-Pinega Formation of the Proterozoic, the stratotype of which was distinguished in the depth interval of 535.75–353.60 m of the borehole Arkhangelsk (Fig. 1). Later on, it was established that *Sabellidites*-like fossils are characteristic of the Neoproterozoic deposits in general and are not suitable for stratigraphic subdivision and correlation (Stankovsky *et al.*, 1990; Gnilovskaya, 1996; Gnilovskaya *et al.*, 2000).

In 1962, the Interdepartmental Conference on Elaboration of Unified Stratigraphic Schemes for the Upper Precambrian and Paleozoic of the Russian Platform conclusively established the Vendian Complex as a specific post-Riphean stratigraphic subdivision. By that time, Igolkina (1959) described a rhythmic succession of beds exposed in the southeastern White Sea area that enabled its correlation with the Vendian stratotype and Redkino Formation of the Moscow syneclise (Aksenov and Igolkina, 1969; Aksenov and Volkova, 1969). The correlation was based on cyclic stratigraphy with reference to marker horizons of volcanic ash and distribution of organic-walled microfossils. Solontsov and Aksenov suggested a correlation of the Vendian Complex of the southeastern White Sea area with the Ust-Pinega and Lyubim formations of central and northern platform areas (Solontsov and Aksenov, 1970; Solontsov *et al.*, 1970; Aksenov *et al.*, 1978). The Ust-Pinega Formation was regarded therewith in the range established by A.I. Krivtsov in the eponymous borehole section and corresponding to the depth interval of 804–520 m (Fig. 1).

The results of geological survey (1965–1985) carried out in the southeastern White Sea area under guidance of Stankovsky showed that the Vendian succession differs here in lithologic and facies characteristics from that described in the central platform areas. In particular, the Ust-Pinega Formation as distinguished by

Solontsov and Aksenov is overlain here by a succession of interbedded reddish brown silty sandstones and maroon brown clays differing in coloration from green rocks of the Lyubim Formation. In addition, perfect exposures and numerous borehole sections exhibit coarsening-upward regressive cycles (Stankovsky *et al.*, 1981, 1985) in contrast to fining-upward transgressive cycles of the Ust-Pinega sedimentary sequence as argued by Solontsov and Aksenov. According to the results obtained, the Ust-Pinega Formation has been divided into members, some of which retained names originally given by Kalberg (Fig. 1).

In 1983, the session of ISC Bureau held in Syktyvkar adopted a stratigraphic scheme for Precambrian deposits of the southeastern White Sea area, in which the Vendian Complex is divided into the Ust-Pinega, Mezen, and Padun formations (Dedeev and Keller, 1986). That scheme ignores, however, the results obtained by Stankovsky and having been of a high practical and scientific importance until present. The Ust-Pinega Formation has been adopted as revised by Solontsov and Aksenov, whereas the Mezen and Padun formations have been proposed without reference to stratotypes. The age of the Padun Formation is problematic.

LITHOLOGIC TYPES OF DEPOSITS

The Vendian succession is composed of clayey, silty, and sandy deposits. Despite the observable lithologic variability and diverse character of bedding and lamination, the deposits are divisible into a limited number of lithologic types. Each of the latter characterizes natural sedimentary bodies (beds) displaying a persistent combination of features, which are indicative of time, genesis, and depositional settings of a given sediment. In addition to the lithological types described below, there are conglomerate, gravelstone, and volcaniclastic beds in the succession, and the carbonate, sulfate, and ironstone concretions.

Distinguished among the Vendian rocks are the following eight lithologic types:

(1) *Thin-bedded mudstone* constituting beds and members (up to 20 m thick); the lamination is visualized by silty laminae, as thin sometimes as one grain, by fine brown sapropel-like films, and by thin interbeds of volcanic ash (Plate I, fig. 2). The latter are variably thick, from 1 or 2 mm to 10 cm. Particular 1-m-thick intervals of mudstone sequence may enclose 4 to 6 ash beds.

(2) *Interbedded siltstone and mudstone* may represent intervals from few centimeters to 4 or 5 m thick; laminae of both rock types are 2 to 3 mm thick in average (Plate I, fig. 3). Siltstone laminae with sharp lower boundaries show fine graded bedding and occasionally fine cross-lamination (Plate I, fig. 5). In general, intercalated siltstone and mudstone laminae are of equal thickness, although one of the laminae type (e.g., fine-bedded siltstone, Plate I, fig. 5) can be thicker than the other one. Sandstone interbeds (5 to 10 mm thick) locally appearing as a third component are considerably thicker than mudstone laminae (1 to 2 mm); they exhibit wavy top surface and are discontinous.

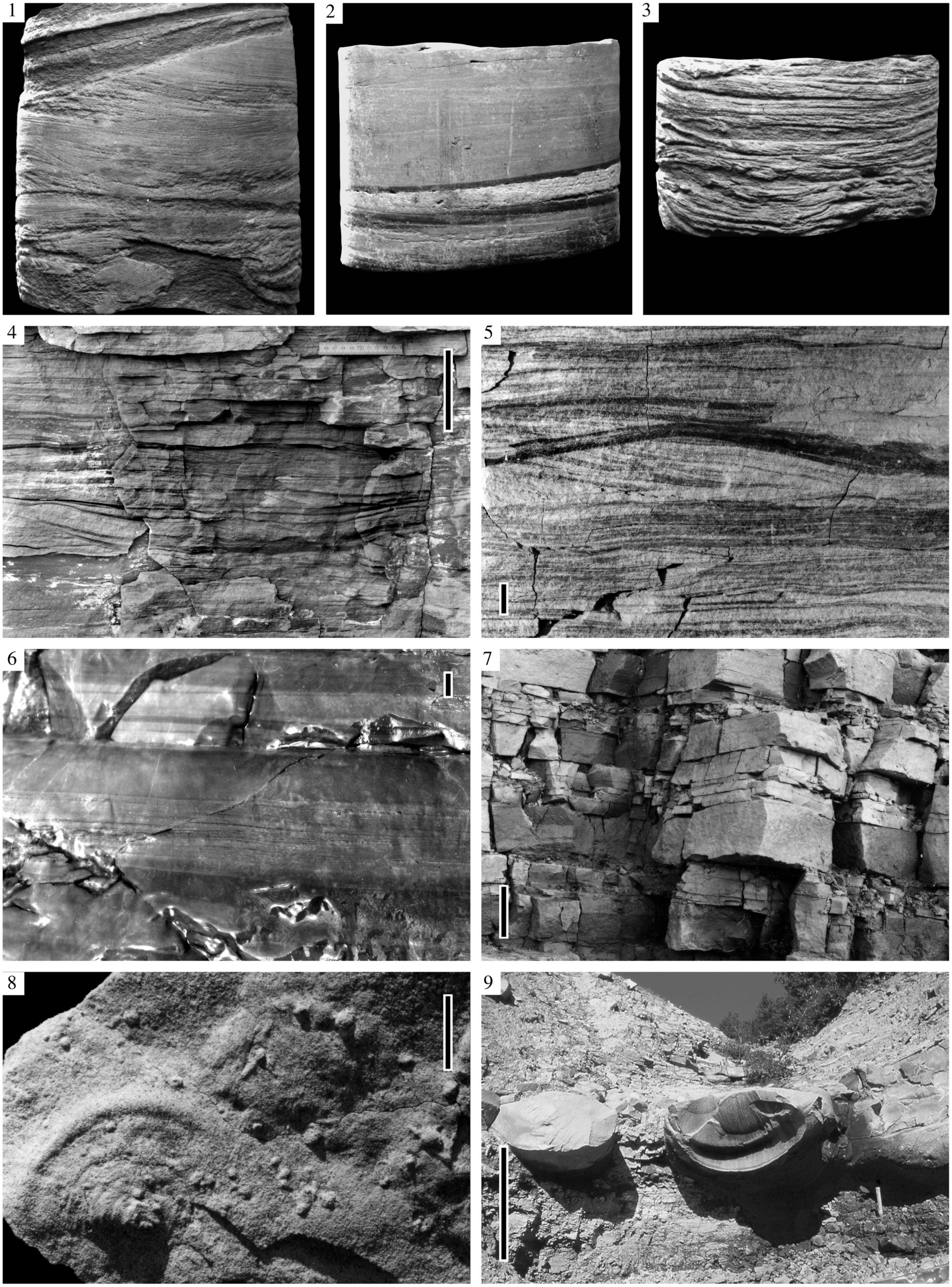
(3) *Fine-grained sandstone with thin horizontal bedding*; this is a type rock of interbeds (5 to 20 cm) or beds (up to 0.5 m thick) within the sequence of interbedding siltstone and mudstone (Plate I, fig. 7). Sole planes of beds are decorated with tool or drag marks and with flute casts, all having a uniform trend. Also typical of sole planes are load casts and accumulations of small mudstone pebbles.

(4) *Fine-grained sandstone with ripple cross-lamination*; the rock is typical of beds 5 to 20 cm thick, which are widespread in the Vendian sequence. The beds are flaggy because of multidirectional cross lamination, and their top surface is wavy (Plate I, fig. 1). They split into flags along shale partings less than 1 mm thick (films on bedding planes), which may grade into thicker shale laminae (some over 10 mm thick). Sole planes exhibit multidirectional tool marks, flute casts, and swing marks. The latter correspond to arcuate scratches and grooves produced by the bottom-anchored objects (e.g., by algae) when they swayed from side to side in turbulent flow (Plate I, fig. 8). The swing marks are either bow-shaped or bimodal in configuration.

(5) *Isolated gutter casts* represent ribbon-shaped thin-bedded sand bodies with erosional base, which originated when sandy material infilled the wide gutters in muddy substratum (Plate II, fig. 1). The casts are up to 0.3–0.4 m thick and up to 1 m wide. Their length is unknown, though steep pinch-outs are frequently visible. The cast formation was associated with scouring and liquefaction of mudstone-siltstone sequence that encloses these bodies (arguments in favor are the erosional contacts and soft deformation of the host deposits). Consequently, the gutters originated under influence of sand-saturated flows, which eroded the non-compacted muddy substratum and became immediately cast by coarser sediments. This is evidenced, in particular, by steep and “overhanging” gutter walls.

(6) *Fine-grained sandstone with hummocky stratification*; these interbeds in mudstone-siltstone sequence are 7 to 10 cm thick and have smooth erosional soles (Plate II, fig. 2). The interbeds consist of several undulatory “series,” each forming the low-amplitude (up to 6 cm) hummocks, the wavelength of which can be as great as 1 m. The hummocks are erosional in origin, because stratification of underlying series is truncated under variable angles.

(7) *Fine- to medium-grained sandstone with planar lamination* constitutes beds (0.1 to 0.5 m thick) and members (up to 10 m thick) extending for a distance of several kilometers (Plate II, fig. 3). Because of planar to gently undulating lamination, the rocks are of a regular flaggy structure. Their beds have smooth soles and bed-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ding planes marked by current-formed parting lineation.

(8) *Medium- to coarse-grained sandstone with multistoried cross-lamination* is characteristic of lenticular beds 2 to 4 m thick, which have erosional soles and represent casts of overflow and distributary channels. The overflow channel casts are up to 10 m wide, having basal packages (up to 30 cm thick) of planar-laminated sandstone with diverse erosion marks at the sole (Plate II, fig. 5), followed by sandstone packages (10 to 15 cm thick) with unidirectional multistoried cross-lamination. Separate cross-laminated series are few centimeters thick in this case. The distributary-channel casts are wider, although their exact width is undeterminable. In distinction from the channel casts, these casts reveal the large-scale trough cross-bedding viewed on a vertical section transverse to flow and the wavy boundary sets viewed on a vertical section parallel to flow. In these casts, cross-laminated series are up to 0.6 m thick (Plate II, fig. 6). In both cast types, accumulations of flattened mudstone pebbles are confined to boundaries between cross-laminated series.

In addition to casts, there are thin (0.1 to 0.5 m) beds of cross-laminated sandstone, which are traceable along the strike over a distance of several kilometers (Plate II, fig. 4). Their pinching-out in lateral direction has not been observed, although it is also possible that they represent deposits of wide (several kilometers across) distributary channels.

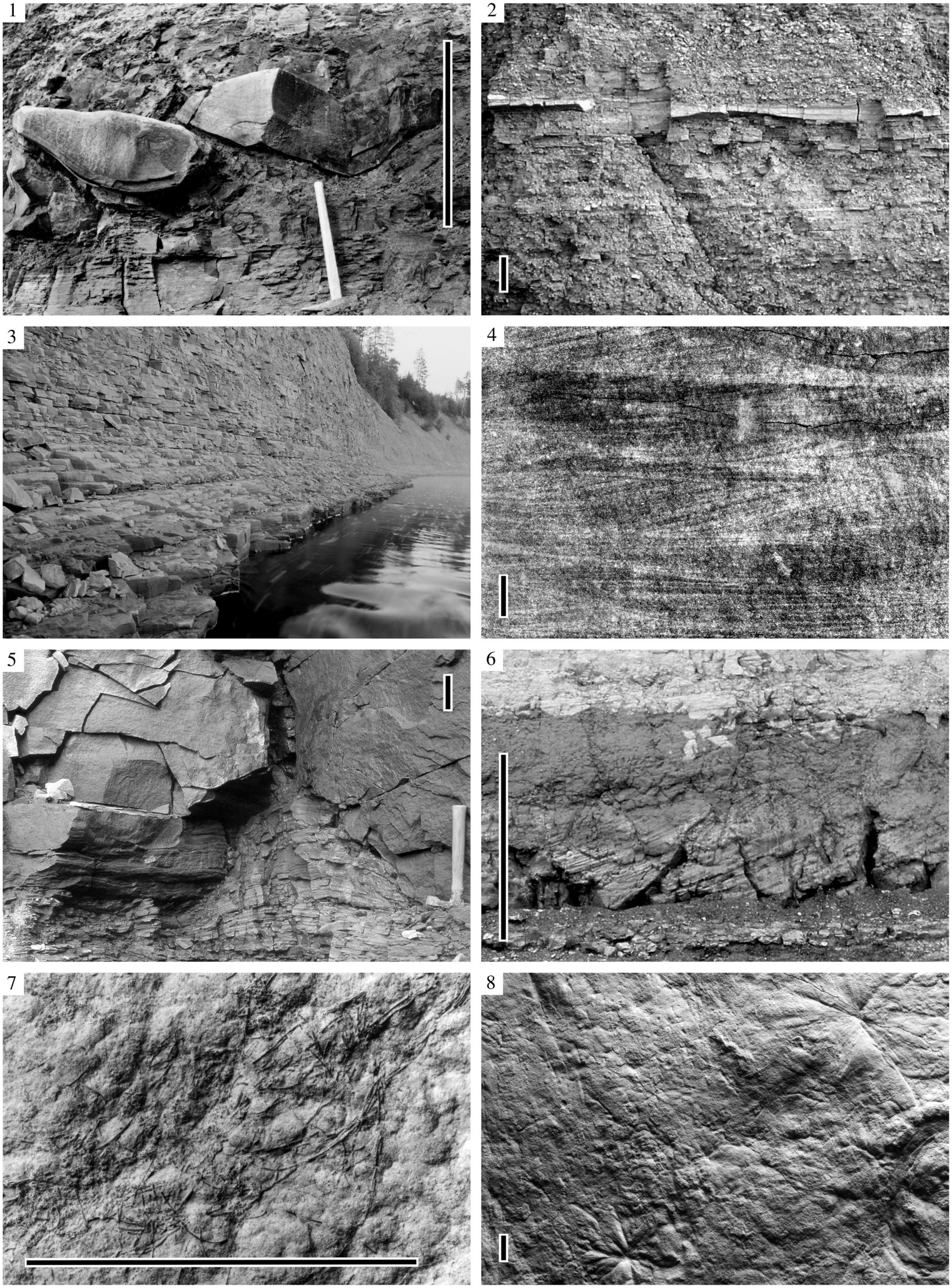
LITHOSTRATIGRAPHY

Exposures and borehole sections of sedimentary cover, which have been studied along the eastern margin of the Baltic Shield, elucidate important details of the Vendian Complex structure. In all the sections, the Vendian succession is divisible into large packages, each differing from the other in the content of sandy material and, sometimes, in coloration. These subdivisions are well traceable within a given facies zone only, but their regular alternation in the succession is persistent and can be used to distinguish the natural parageneses of lithologic types characterizing individual sedimentary cycles and their stratigraphic succession (Fig. 4) that is used in this work as a basis for subdivision and correlation. Sedimentary cycles recognizable in the Vendian succession range in scale from microcycles characterizing texture of separate lithologic types to mini-, meso-, and megacycles, which exemplify corresponding periods of sedimentation (Fig. 4).

Vendian deposits of the southeastern White Sea area have turned out to be of a more complex lithology and facies variability than it was thought before. For instance, a thick sandstone sequence terminating sections in the Onega Peninsula (Fig. 2) was erroneously interpreted as signifying the beginning of a transgressive cycle and correlated with the Mezen (Erga in this work) Formation (Aksenov, 1985; Stankovsky *et al.*, 1985). Recent data (Grazhdankin and Bronnikov, 1997) showed, however, that this sequence is coarsening upward, in contrast to fining-upward sediments of the Erga Formation, and terminates the corresponding sedimentary cycle. In addition, drilling results obtained in the Onega Peninsula changed views on stratigraphic position of cross-bedded gravelstone beds, which were originally interpreted as early transgressive deposits of the Ust-Pinega Formation (Solontsov *et al.*, 1970) and then attributed to basal Tamitsa Member of the latter (Stankovsky *et al.*, 1990) thereby representing marine ingression event (Fig. 1). New boreholes drilled in the Onega graben demonstrate that these gravelstones form progradation wedges in sandstone fill of that graben and pinch out toward the graben axial zone (Fig. 3). According to textural peculiarities, the host sandstones are similar to underlying Upper Riphean deposits. Consequently, the gravelstone wedges are of the same age, as one can judge from their genesis and structural position.

Admitting that priority and stability of stratigraphic nomenclature are important, I suggest to restore the formation names originally used by Kalberg in her reports on stratigraphy of the southeastern White Sea area, though stratigraphic ranges of the subdivisions must be changed according to new data (Fig. 1). In their new ranges, each of the Lyamtsa, Verkhovka, and Zimnie Gory formations on the one hand, has persistent lithologic-facies characterizations, and on the other hand, represent an integral succession. Kalberg suggested the names after investigation of known natural exposures known at that time and core sections recovered from boreholes Nenoksa and Arkhangelsk (unpublished report of 1950 by Kalberg and Frumkina). Stankovsky and his colleagues used the same names, when they divided the Ust-Pinega Formation into members, which are still used in publications and geological practice (Fig. 1). The term Erga Formation is introduced to

Plate I. Principal lithofacies of the Vendian Complex, southeastern White Sea area: (1) sandstone interbed with ripple cross-lamination, Borehole C18 (depth interval 179.0–182.0 m, core diameter 52 mm); (2) thin-bedded mudstone with volcanic ash interlayer (light colored), Lyamtsa Formation, Borehole C17 (depth interval 300.0–305.4 m, core diameter 52 mm); (3) interbedded siltstone and mudstone, Lyamtsa Formation, Borehole C11 (depth interval 121.0–126.0 m, core diameter 52 mm); (4) flute casts in interbedded siltstone and mudstone, Verkhovka Formation, Zimnie Gory site (scale bar 0.1 m); (5) siltstone interlayer with cross-lamination in interbedded siltstone and mudstone, Verkhovka Formation, Zimnie Gory site (scale bar 10 mm); (6) thin-bedded siltstone Zimnie Gory Formation, Zimnie Gory site (scale bar 10 mm); (7) flaggy stratification of alternating fine-grained sandstone beds and interbedded siltstone and mudstone, Verkhovka Formation, lower reaches of the Syuzma River (scale bar 0.1 m); (8) swing marks at the base of sandstone bed, Zimnie Gory Formation, Zimnie Gory site (scale bar 10 mm); (9) isolated bodies produced by syngenetic deformations in fine-laminated sandstone bed; Erga Formation, Zimnie Gory site (scale bar 1 m).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replace the Mezen Formation having a homonym. The term “Mezen Formation” was earlier introduced in the Upper Permian deposits of Mezen syneclise in 1969 as an equivalent of the synonymous horizon established by A.A. Malakhov in 1940 (see in Molin *et al.*, 1986).

Age of the Padun Formation has not been determined (Sivertseva and Stankovsky, 1982), and this subdivision is omitted from consideration in this work. It is admissible that the indicated formation includes Cambrian strata penetrated by boreholes in the study area (Popov and Gorjansky, 1994). The Vendian upper boundary provisionally corresponds to the base of a thick sandstone member (2.5 m) with planar lamination and conglomerate deposit. The boundary is observable in the Myandovo Canyon (Zolotitsa River middle reaches), where it corresponds to the base of Zolotitsa Beds of the Padun Formation (Stankovsky *et al.*, 1990).

Lyamtsa Formation has been established by Kalberg in coastal cliffs near the village Lyamtsa and in the borehole Arkhangelsk, depth interval of 533.9–435.9 m (Fig. 2), as a unit underlying the Arkhangelsk Formation of sandy deposits (the same borehole, depth interval of 435.9–372.5 m). Both formations represent an integral sedimentary megacycle of coarsening-upward deposits, and it is reasonable to consider them coupled under the name of Lyamtsa Formation. With this new range, the formation spans interval of the Lyamtsa and Arkhangelsk beds in the stratigraphic scheme by Stankovsky (Fig. 1).

The section exposed in coastal cliffs of the Lyamtsa River mouth can be retained as the formation stratotype (Fig. 3), because the general succession of deposits is established in the borehole drilled near the exposure in 1950, which penetrated the formation base at the depth of 77.4 m (Zoricheva, 1963). A candidate for hypostratotype is the depth interval of 214–54 m in the borehole S18 drilled in the right side of the Agma River valley by the Syuzma Geological Party in 1996. The formation thickness is rather persistent, equal to 160 m in the type section (Fig. 2).

The formation lower boundary corresponds to the base of gravelstone package, which displays graded bedding and is overlain by a member (12 to 18 m thick) of variegated thin-laminated mudstone, brown to gray in coloration and hosting the volcanic ash interlayers (Plate I, fig. 2). Toward the northeast (borehole Arkhangelsk), the mudstone grades into a variegated sequence of interbedded siltstone and mudstone (report of 1951 by A.I. Lebedintsev), the mudstone component of which is prevailing (Fig. 2). The lower boundary stratotype is suggested to be in the borehole 18 (Fig. 2) at the depth level of 214 m corresponding to the base of thin (0.4 m) package of light gray gravelstone.

A uniform rhythmical interbedding of thin variegated siltstone and mudstone beds characteristic of the formation (Plate I, fig. 3) is interrupted by progradation wedges enclosing interlayers (20 to 140 mm) of gray sandstone with ripple cross-lamination (Plate I, fig. 1). Spatial position of wedges is reconstructed based on layer-by-layer correlation of borehole sections (Figs. 2 and 3). This structural peculiarity offers a possibility to divide formation into three members representing a succession of sedimentary mesocycles, the thickness of which progressively increases upward in the section (24, 50, and 86 m, respectively, in the borehole section C18; Fig. 2). The progradation wedges are situated near the shield slope, and away from the latter, the cyclic structure of the formation is not as distinct (Fig. 3). Each mesocycle represents a regressive succession, the abundance and thickness of sandstone interlayers in which grow upward. The total thickness of sandstone interlayers increases in each successive mesocycle (Fig. 2).

The interbedding siltstones and mudstones bear phytoleims of vendotaenian algae, organic-walled remains *Beltanelloides sorichevae* Sokolov, and wrinkled tubular sheaths resembling *Sabellidites.* Swing marks widespread on sole planes of rare sandstone interlayers are broadly arched or bimodal in morphology. Remains of Ediacara-type biota are rare in the Lyamtsa Formation and occur mostly in the upper sandy portion of the upper mesocycle (Fig. 4).

Verkhovka Formation was established by Kalberg in the borehole Arkhangelsk (depth interval of 372.5–299.6 m; Fig. 2). Its stratotype has not been indicated, but the name derives from the eponymous river valley, where (Kalberg, 1940) she studied outcrops. The boundary with overlying Zimnie Gory Formation was placed at the base of a sandstone member (depth level of 299.6 m in the borehole Arkhangelsk; Fig. 2). Exposures studied in the Onega Peninsula show that this member is terminal one in a thick (140 m) regressive mesocycle, and it exhibits gradual transition into the underlying deposits of the Verkhovka Formation (Figs. 3 and 4). Therefore, the revised formation range

Plate II. Principal lithofacies of the Vendian Complex, southeastern White Sea area: (1) isolated gutter casts at the boundary between the Zimnie Gory and Erga formations, Zimnie Gory site (scale bar 1m): (2) sandstone interlayer with hummocky stratification in interbedded siltstone and mudstone, Verkhovka Formation, Letnii Coast of the White Sea (scale bar 0.1 m); (3) thick sandstone member with planar lamination, Verkhovka Formation, lover reaches of the Solza River (apparent thickness 15 m); (4) multistoried cross-lamination, Zimnie Gory Formation, Zimnie Gory site (scale bar 10 mm); (5) two waterways recorded at the base of sandstone channel cast, Erga Formation, Zimnie Gory site (scale bar 0.1 m); (6) longitudinal section of a channel cast with basal cross-laminated sandstone grading upward into sandstone with planar lamination, Erga Formation, middle reaches of the Zolotitsa River (scale bar 1 m); (7) pyritized remains of algal filaments on a shagreen under surface of thin-bedded sandstone, Erga Formation, Zimnie Gory site (scale bar 10 mm); (8) deformation marks at the shagreen under surface of siltstone bed in the interbedded siltstone-mudstone sequence, Verkhovka Formation, Zimnie Gory site (scale bar 10 mm).

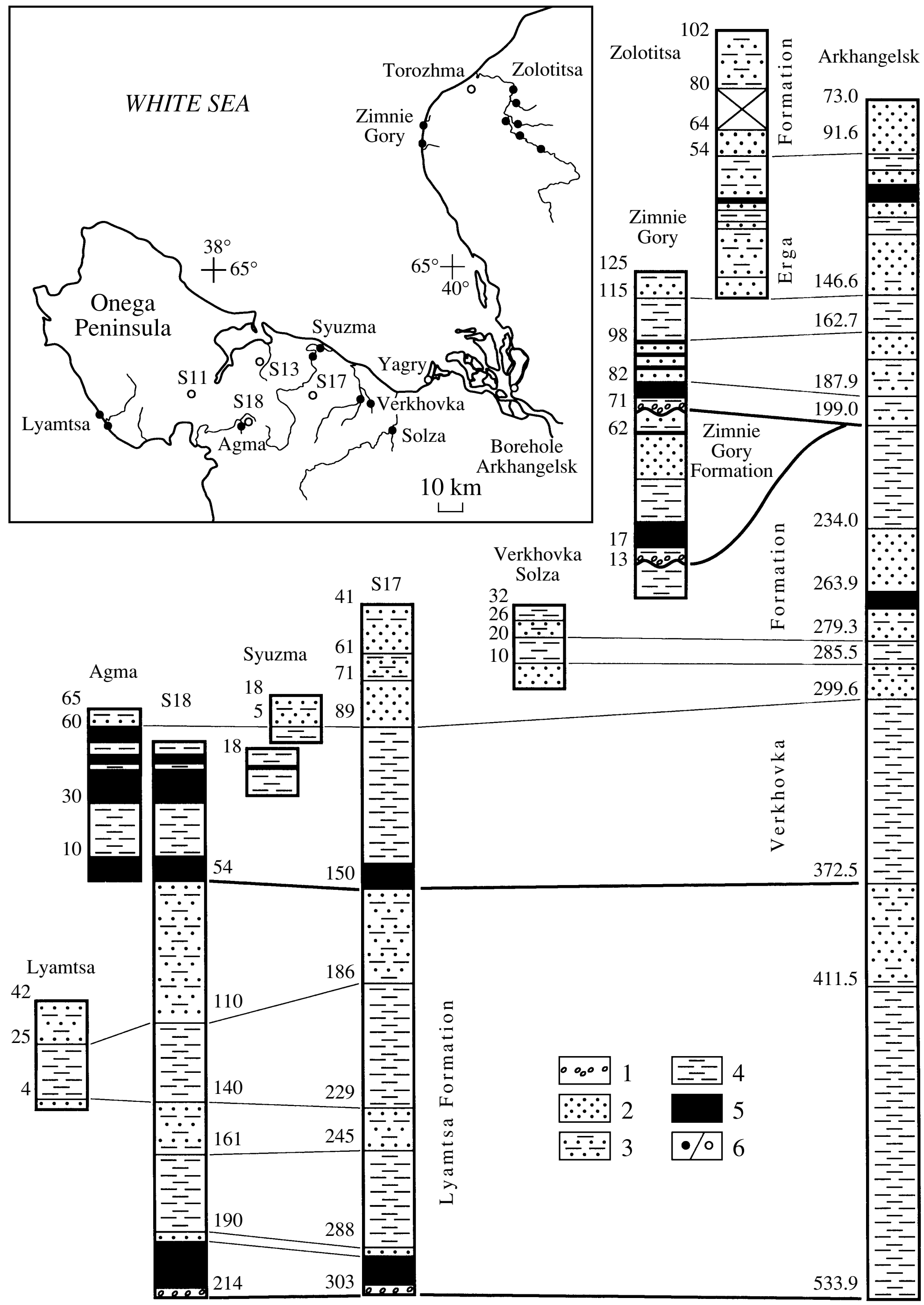

Fig. 2. Geographic localities and lithostratigraphy of Vendian sections studied in the southeastern White Sea area: (1) gravelstone; (2) sandstone; (3) interbedded sandstone, siltstone, and mudstone; (4) interbedded siltstone and mudstone; (5) mudstone; (6) exposure/borehole (section Arkhangelsk is plotted based on unpublished data of A.I. Lebedintsev, 1951).

is greater than the original one and includes a part of Zimnie Gory Formation in the former understanding of Kalberg (Fig. 1). The new range spans the interval of Verkhovka and Syuzma beds in the scheme by Stankovsky (Fig. 1). The depth interval of 109.8–81.0 m in the borehole Yagry, which has been attributed by Kalberg to the transitional Yagry Formation (Fig. 3), is well correlative with the middle portion of the Verkhovka Formation. Accordingly, I consider the term "Yagry Formation" as a synonym of the latter. The most complete section of the Verkhovka Formation (170 m; Fig. 2) has been penetrated by the borehole Arkhangelsk (Fig. 2), the core samples of which are lost.

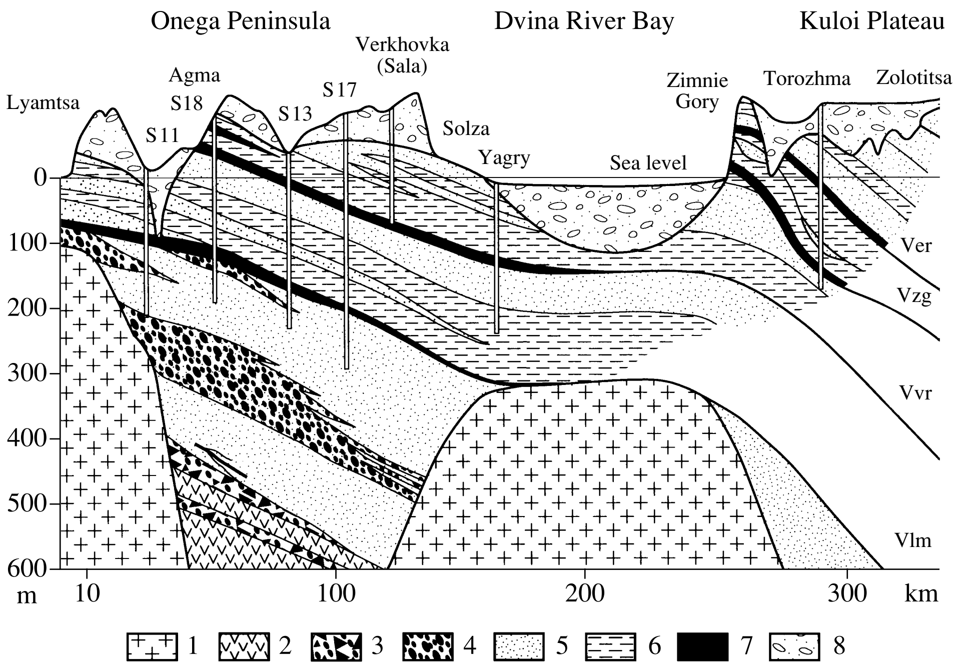

Fig. 3. Suggested architecture of the Vendian and underlying deposits in the southeastern White Sea area: (1) crystalline basement; (2) basalt; (3) volcanic breccia; (4) gravelstone; (5) interbedded sandstone, siltstone, and mudstone; (6) interbedded siltstone, and mudstone; (7) mudstone; (8) Quaternary deposits. Letter symbols denote Lyamtsa (Vlm), Verkhovka (Vvr), Zimnie Gory (Vzg), and Erga (Ver) formations. Borehole sections are described by Kalberg (1937; Yagry and Sala), Zoricheva (1963, Lyamtsa), Stankovsky *et al.* (1990, Torozhma).

The Verkhovka Formation represents a regressive megacycle. Its lower boundary is established at the level of abrupt transition from interbedding gray sandstone, siltstone, and mudstone of the Lyamtsa Formation to overlying member of maroon fine-laminated mudstone with volcanic ash beds. The lower boundary stratotype is suggested to be fixed at the base of maroon mudstone member (10 m thick) viewed in exposure of the Agma Creek mouth site. U–Pb age of zircons from the ash bed (12 mm) located in that exposure 0.5 m above the formation base is 558 ± 1 Ma (Martin *et al.*, 2000).

The megacycle consists of two mesocycles, the lower of which is exposed in outcrops of the Onega Peninsula (Fig. 2), where its lower half viewed in the Agma Creek outcrops (left tributary of the Nizhma River) represents the alternation of members (4 to 30 m thick) composed either of variegated fine-laminated mudstone, or of interbedded greenish gray siltstone and mudstone. The latter lithologic type also encloses thin (10 to 15 cm) lenticular sandstone interbeds displaying hummocky stratification (Plate II, fig. 2) and small (30 to 50 mm) gutter casts. Eastward, the basal mudstone member grades into facies of interbedded mudstone and siltstone. Close to the base of the lower mesocycle, there are widespread sulfide, gypsum, and carbonate concretions viewed in outcrops of the Agma, Syuzma, and Letnii Coast localities and observed in the borehole S17, Sala, and Yagry. The flattened (disk-like) shape of concretions and cone-in-cone structures characteristic of carbonate ones imply that they were formed in partially compacted sediments.

The upper sandy interval of the lower mesocycle is of a complex structure. It has been penetrated by borehole S17 (depth range of 89–41 m) and is fragmentary exposed in the Syuzma, Agma, Verkhovka, and Solza river valleys (Figs. 2 and 3). In western sections, the interval is composed of sandstone beds striking NE–SW and well studied in a small outcrop located 5 km upstream of the Syuzma River mouth (Fedonkin, 1981). The basal, purple-gray thin-bedded siltstone encloses here lenticular gutter casts (0.3–0.4 to 1.2 m wide) composed of greenish gray, fine- and cross-laminated sandstone. The main stratified sequence (Plate I, fig. 7) is composed of lenticular sandstone beds (0.1 to 0.4 m thick), which display either thin horizontal bedding, or multistoried cross-lamination, and diverse erosion marks at their soles. Unimodal swing marks with an acute arching angle have been viewed on one of the soles. Thicker (10 m) members of planar-laminated sandstone are rather persistent along the strike, traceable for a distance as long as dozens of kilometers (Plate II, fig. 3).

Composition and structure of the interval under consideration change considerably across the beds' strike, toward the southeastern Verkhovka and Solza localities, where the massive sandstone beds either pinch out, or grade into layers of interbedded sandstone, siltstone, and mudstone so that the total proportion of sandy

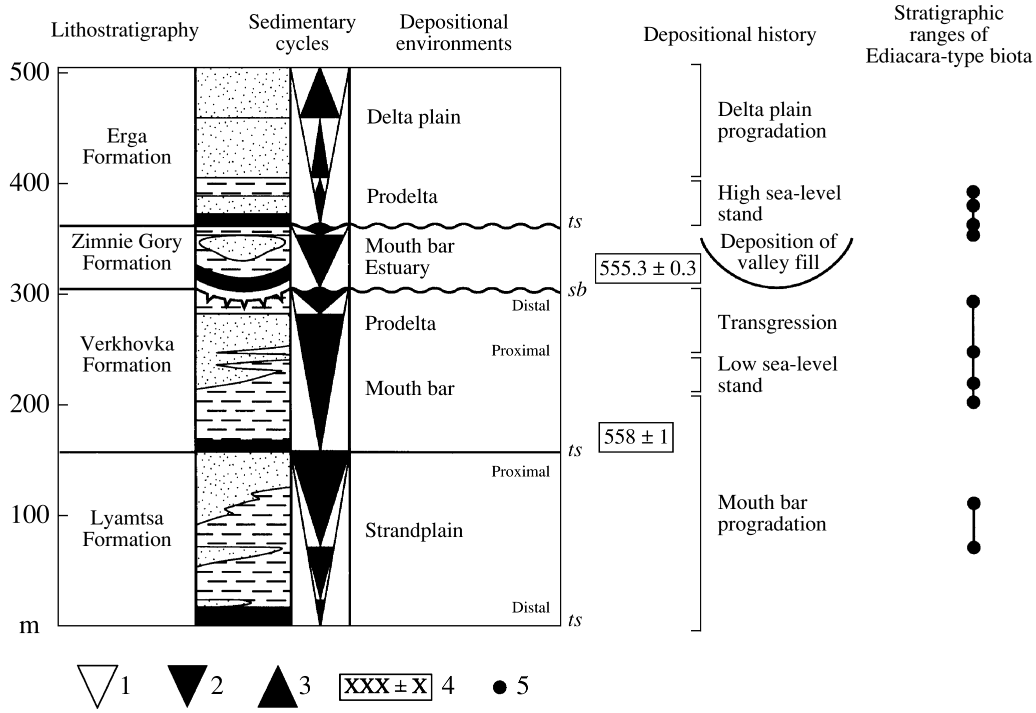

Fig. 4. Lithostratigraphy, depositional environments and formation history of Vendian deposits in the southeastern White Sea area: (1) regressive megacycle; (2) regressive mesocycle; (3) transgressive mesocycle; (4) radiometric age, Ma; (5) occurrence of diverse Ediacara-type biota; (*sb*) sequence boundary; (*ts*) transgressive boundary (other symbols as in Fig. 3).

material is lower here (Fig. 3). Characteristic of this interval, lenticular thin-bedded sandstone beds (0.3 to 0.5 m thick) have erosional soles and strike NE–SW, but the strata are locally deformed into folds and various slump structures. The deformed units occur between the undistorted ones, and the general style of deformations is irregular, changing from site to site (Grazhdankin and Bronnikov, 1997).

In outcrops of the Zimnie Gory area, an interval (0–13 m; Fig. 2 and Plate I, figs. 4 and 5) of greenish gray interbedded siltstone and mudstone at the base of the section encloses interlayers of cross-laminated siltstone. Higher in the sections, there are sandstone interbeds (5 to 10 cm thick) with ripple cross-lamination. It is difficult to define the exact stratigraphic position of these rocks, because the area under consideration is situated far away from the Onega Peninsula, deep boreholes have never been drilled here, and the contact with overlying strata is erosional (Figs. 2–4). In this paper, they are correlated with the interval of 234.0–199.0 m of borehole Arkhangelsk (unpublished report of 1951 by Lebedintsev) and attributed to the upper mesocycle of the Verkhovka Formation (Fig. 2).

Ediacara-type remains are irregularly distributed in the described formation. Rare fossils are found near the base of the lower mesocycle and are associated with the drag and deformation marks on basal surfaces of sandstone beds with hummocky stratification. Pyritized remains of *Sabellidites*-like tubular morphotypes, which have been discovered by Kalberg, are known from the fine-laminated mudstone. Sandstone beds exposed in the Agma and Syuzma river valleys yield a peculiar assemblage of three-dimensional Ediacara-type fossils (Fedonkin, 1981). A diverse assemblages of fossils are also known from higher strata of interbedded siltstone and mudstone with sandstone interlayers, which are exposed in the Verkhovka and Solza river valleys (Grazhdankin and Bronnikov, 1997), and from the upper mesocycle exposed in the Zimnie Gory cliffs (Fedonkin, 1981; Fig. 4).

Sections, which are exposed near the base of these cliffs and in the Agma, Syuzma, Verkhovka, and Solza river valleys, comprise almost complete succession of the formation and can be accepted for the composite lectostratotype of the latter.

Zimnie Gory Formation has been distinguished by Kalberg in synonymous coastal cliffs and correlated with the depth interval from 299.6 to 146.6 m of the borehole Arkhangelsk (Fig. 2). In this work, its range is changed based on new data. In the new understanding, the formation is bounded by the lower and upper erosion surfaces and spans the interval attributed by Stankovsky to the Vaizitsa and Zimnie Gory beds (Fig. 1). In the northeast of study area, deposits of the formation are distributed irregularly. Being undetected in the borehole Arkhangelsk, the formation is 58 m thick in the Zimnie Gory section (interval from 13 to 71 m; Fig. 2) and 125 m thick in the borehole Torozhma (depth interval of 261.5–134.9 m; Fig. 3) that was drilled by the Tova Geological Party 26 km northeastward of the Zimnegorskii lighthouse in 1982.

The formation lower boundary is established at the level of abrupt transition from greenish gray interbedded siltstone and mudstone of the Verkhovka Formation to variegated deposits with beds and members of maroon thin-laminated mudstone. Above this erosional boundary, there are lenticular beds (10 to 20 cm thick) of gravelstone and conglomerate. The overlying interval of variegated rocks is composed of sandstone, siltstone, and mudstone exhibiting the wavy and lenticular interbedding (interval from 13 to 17 m in the Zimnie Gory section; Fig. 2). Characteristic of lenticular siltstone and sandstone beds is multidirectional cross-lamination. These beds with erosion soles and wavy upper boundaries are thicker (2 to 6 cm) than the mudstone beds. In addition, the interbedded member encloses isolated gutter casts (15 to 20 cm thick), which are composed of interbedded sandstone and mudstone.

The upper boundary of the described unit is erosional, with scours locally as deep as 4 m. The overlying member (10 m thick) is composed of variegated, maroon to bluish gray thin-laminated mudstone with volcanic ash intercalations. The basal ash bed is conformable to uneven surface of underlying deposits. Ash beds are up to 10 cm thick in scours and pinch out approaching walls of the latter. U-Pb age of zircons from one of the interlayers, which has been sampled 2 m above the formation base in an outcrop near the Medvizhii Creek mouth is 555.3 ± 0.3 Ma (Martin *et al.*, 2000).

A considerable portion of the formation (up to 30 m thick) is composed of purple-gray thin-bedded siltstone (Plate I, fig. 6) with lenticular sandstone intercalations displaying ripple cross-lamination and swing marks on the soles (Plate I, fig. 8). Being rather uniform in the type section, the formation has variable structure in southern exposures (between the Zimnegorskii lighthouse and Erga Creek). Its upper interval (18 m) is represented here by gray sandstone beds of diverse facies affinity (Igolkina, 1959). The sandstone members (up to 2 m thick) comprising rocks with thin planar- and cross-lamination alternate with thin-laminated siltstone members of a comparable thickness, and the whole interval is of a rhythmic structure. The normal succession of beds is locally disturbed by slump structures. Ripple cross-lamination is not characteristic of these rocks. The interval under consideration corresponds to a regressive succession: thin sandstone beds with multistoried cross-lamination are typical of its lower part, whereas the upper one is composed of thick sandstone beds displaying thin planar lamination.

The upper part of the formation (interval from 62 to 71 m in the Zimnie Gory section; Fig. 2) composes a regressive sequence beginning with a persistent basal unit (3 to 4 m thick) of dark gray thin-laminated mudstone with sapropel-like films. The unit has gradual transition to overlying greenish gray siltstone and mudstone, thin alternating beds of which enclose lenses of gray thin-bedded sandstone. This sequence is comparable with the member of interbedded siltstone and mudstone that has been penetrated by the borehole Torozhma (depth interval of 208.3–134.9 m; Fig. 3) and represents a similar regressive sequence (report of 1985 by Stankovsky and his colleagues).

Rare Ediacara-type fossils are confined in the formation section to the upper sequence of interbedded siltstone and mudstone. In addition, the clay unit near the formation base has yielded phytoleims of algae (M.V. Leonov, personal communication, 2001) and *Beltanelloides* impressions.

The exposure of Vendian rocks near the Elovyi Creek mouth is suggested to be the lectostratotype of the Zimnie Gory Formation. The lower boundary stratotype corresponds here to the under surface of maroon fine-laminated mudstone bed (1 m thick) with basal gravelstone lenses.

Erga Formation introduced instead of the Mezen Formation spans the interval of Egra and Mela beds in the scheme by Stankovsky (Fig. 1). Like the synonymous beds, it has got the name after the eponymous creek (Zimnie Gory area), because characteristic rocks of the formation are exposed near the mouth of the latter. Typical of the formation representing a coarsening-upward sedimentary megacycle (150 m thick) is a complex interbedding of variegated sandstone, siltstone, and mudstone. The lower boundary of the subdivision is characterized by erosional scours (1 to 5 m deep), the fine-grained sandstone fill of which encloses pebbles occurring in the imbricated position within the matrix. In the stratigraphic succession the boundary corresponds to the first appearance of yellowish gray sandstone with gravel and pebbles.

Three transgressive mesocycles (45 to 55 m thick) are distinguishable in the formation section. The lower one exposed in coastal cliffs of the Zimnie Gory area (interval from 71 to 115 m; Fig. 2) consists of three persistent members. In its lower part, the lower member (interval from 71 to 82 m) is composed of interbedded sandstone, siltstone, and mudstone (2 to 3 m), which enclose large gutter casts (Plate II, fig. 1). Ripple cross-lamination is characteristic of their basal beds. The whole member represents a fining-upward sequence, because the indicated rocks have gradual transition to overlying gray mudstone (8 to 9 m) that becomes variegated, from brown to gray, in the uppermost portion.

The middle member (interval from 82 to 98 m) is divisible into persistent cyclothems 5 to 6 m thick (Fig. 2). At the base of each cyclothem, there are gutter casts and lenticular beds (up to 0.5 m thick) of gray sandstone with ripple cross-lamination. They grade upward into thin-interbedded siltstone and mudstone with sandstone interlayers followed by fine-laminated mudstone. This succession is locally deformed into folds and various slump structures, some of which have been erroneously interpreted as gutter casts (Grazhdankin and Ivantsov, 1996, Fig. 2). In contrast to slump pillows, the gutter casts are elongated in shape and represent erosional incisions.

The upper member (interval from 98 to 115 m) reveals thin wavy interbedding of greenish gray sandstone, siltstone, and mudstone. Sandstone beds with characteristic ripple cross-lamination enclose accumulations of flattened mudstone pebbles. In addition, there are isolated gutter casts (10 to 15 cm) and peculiar lenticular beds (up to 1.8 m) of planar- and cross-laminated sandstone (casts of distributary channels, Plate II, fig. 5), which occupy several levels in the interbedded sequence.

Beginning from the middle mesocycle (the level of 115 m in the Zimnie Gory section; Fig. 2), sandstone beds of the Erga Formation are colored red, bearing large siderite concretions, whereas the interbedded siltstone and mudstone become variegated (purple, bright-brown, yellow, to orange). The same changes in coloration are recorded at the depth level of 146.6 m in the borehole Arkhangelsk (report of 1951 by Lebedintsev; Fig. 2). The middle mesocycle is exposed in the Zolotitsa (Zimnyaya) River lower riches and along the Temnyi Creek, the right tributary of that river (interval from 0 to 54 m of the Zolotitsa section, Fig. 2). Basal beds (2 m) of the mesocycle are composed of sandstone with planar bedding and current-formed parting lineation. The overlying part is represented by thin-interbedded sandstone, siltstone, and mudstone, which enclose lenticular beds (up to 2.5 m) representing gutter casts of medium- to coarse-grained sandstone composition, which reveal planar and cross lamination and enclose flattened mudstone pebbles (Plate II, fig. 6). In the upper part of the mesocycle, there are beds (up to 1.2 m) and members (up to 6 m) of dark brown fine-laminated mudstone. Ripple cross-lamination and ripple marks are characteristic of rocks constituting the mesocycle.

The upper mesocycle is exposed further upstream along the Zolotitsa River and its right tributary, the Kamennyi Creek (interval from 54 to 102 m of the Zolotitsa section, Fig. 2). It corresponds to the distinct fining-upward sequence and resembles the middle mesocycle.

The assemblage of Ediacara-type remains that is the most diverse among others known from the southeastern White Sea area is confined to the lower part of the Erga Formation, being especially characteristic of the middle member of the lower mesocycle (Grazhdankin and Ivantsov, 1996; Ivantsov, 1999). Above this interval, fossils have not been encountered. In the Erga Formation, there is recorded a transition from the Redkino to Kotlin assemblage of organic-walled microfossils (Ragozina and Sivertseva, 1990). Microfossils known from the Lyamtsa, Verkhovka, Zimnie Gory, and lower Erga deposits are characteristic of the Redkino assemblage (Sivertseva and Stankovsky, 1982; Ragozina and Sivertseva, 1990; Stankovsky *et al.*, 1990). Microfossils *Pomoria rhomboidales* (Sivertseva), which have been described from the upper member of lower mesocycle of the Erga Formation (depth level of 57 m in the borehole Torozhma, Fig. 3), are widespread in the upper Kotlin beds of the Moscow syneclise (Ragozina and Sivertseva, 1990; Kuz'menko and Burzin, 1996).

The formation neostratotype is suggested to be corresponding to a sequence of sections exposed in the Zimnie Gory area (between the Zimnegorskii lighthouse in the north and Erga Creek mouth in the south) and along the Zolotitsa River, which characterize almost completely the rock succession described above. The candidate for the lower boundary stratotype is the under surface of member composed of interbedded siltstone and mudstone, which encloses gutter casts of sandstone composition and is exposed in outcrops of the Erga Creek mouth.

Cyclicity

Mesocycles ranging in thickness from 40 to 80 m are most easily distinguishable in the studied sections and can be divided in two types with different lithologies and bed successions. Basal portions of the regressive mesocycles are composed of fine-grained sediments exclusively (e.g., of thin-laminated mudstone). These sediments are overlain by interbedded siltstone and mudstone sequence that encloses sandstone interlayers with thin planar- or ripple cross-lamination, the abundance and thickness of which increase progressively upward. Mesocycles of this type are established in the Lyamtsa, Verkhovka, and Zimnie Gory formations (Fig. 4). In the transgressive mesocycles, basal sandstone beds reveal planar bedding near the base, fine- and cross-lamination in the middle interval, and ripple cross-lamination in the upper one. They are overlain by a fining upward interbedded siltstone and mudstone sequence. The transgressive mesocycles are established in the Erga Formation. Thus, the boundary between the latter and the underlying Zimnie Gory Formation corresponds to the sudden change in morphology of sedimentary mesocycles of the Lyamtsa, Verkhovka, and Zimnie Gory formations (Grazhdankin and Bronnikov, 1997; Fig. 4).

Mesocycles are divisible in lesser sedimentary cycles (10 to 20 m thick), which can be distinguished, for instance, in succession of the Verkhovka Formation rocks (Grazhdankin and Bronnikov, 1997), though it is difficult to trace them for a long distance, because the outcrops are not so well exposed here. Minicycles are clearly recognizable in the lower part of the Erga Formation, and this interval of the Zimnie Gory section is divisible into corresponding persistent members. The latter are composed of elementary cyclic units (5 to 6 m thick) resembling cyclothems of deltaic deposits. These cyclothems of fining-upward structure have been traced along the Zimnii Coast of the White Sea for a distance of 35 km, from the Zimnie Gory site to the Zolotitsa

River mouth. They are of persistent thickness and lithologic composition.

Combinations of mesocycles represent larger megacycles 120 to 160 m thick, which are traceable over great areas. The Vendian succession of the study region is divided into four megacycles of this kind, which correspond to the formation described above and are in general of the coarsening-upward structure (Fig. 4).

DEPOSITIONAL ENVIRONMENTS

Data presented above enable reconstruction of depositional environments during accumulation of the Vendian Complex.

Depositional environment of the Lyamtsa Formation. It is likely that most distal deposits of the formation are represented by fine-laminated mudstone. Their undisturbed fine lamination (Plate I, fig. 2) points to precipitation of suspended sedimentary material in low energy conditions. Like in the present-day seas (Oertel and Dunstan, 1981; Holmes, 1982; Sahl *et al.*, 1987), the suspended material could be formed in offshore settings and, still floating owing to difference in temperature and salinity, it could be sorted by coastal currents and during strong storm events and then transported away from the shore into depositional settings. The upper silty and muddy layers of bottom sediments could be recurrently suspended under influence of storm waves and, being captured by bypassed flows, the material was gradually transported toward a zone, where the oscillation wave rate was lower. The progressive sorting in wave flows (Swift *et al.*, 1991) resulted in deposition of coarser silty particles within the proximal zone, where the thin-interbedded siltstone-mudstone sequence (Plate I, fig. 3) characterizing the greater part of the formation section was formed. Thin sandstone interlayers with ripple cross-lamination (Plate I, fig. 1), which occur close to the shield slope, the widely arcuate or bimodal swing marks on their soles, and multidirectional current-formed parting lineation are important arguments in favor of the wave mechanism of clastic material transport. Fine-laminated mudstone accumulated in distal settings inaccessible for the storm wave impact.

Thus, the greater portion of the formation was deposited in strandplains above the storm wave base. The perfect sorting and indications of wave reworking allow me to interpret the interbedded siltstone-mudstone sequence with sandstone interlayers as storm deposits. Widespread algae phytoleims and swing marks on the interlayers' soles imply that strandplains were situated within the photic zone and inhabited by algae. Progradation wedges of sandstone reflect most likely a higher rate of wave reworking and sediment transport on shoals, and the progradation of strandplains away from the eastern slope of the Baltic Shield (Figs. 2 and 3).

Depositional environment of the Verkhovka Formation. The base of the formation marks sea level rise and abrupt environmental changes. Strandplains of the terminal Lyamtsa time turned into relatively calm settings of predominantly clayey sedimentation (boreholes 17 and 18, and the Agma Creek section; Fig. 3), and zone of wave flow influence shifted to the northeast, where deposition of interbedded siltstone-mudstone sequence was again in progress (Arkhangelsk).

The further development was associated with gradual return of offshore settings with storm-wave sedimentation regime, as it is evident from a thick (50 m) interbedded siltstone-mudstone sequence occupying the lower formation part in the Onega Peninsula (Fig. 3). Rare and thin sandstone interlayers in these deposits have hummocky stratification (Plate II, fig. 2) that used to be regarded as indicative of wave activity. However, the influence of oscillating flow is not the only factor responsible for origin of this lithologic type (Allen, 1985), because progressive gravity waves should interact in this case with a unidirectional turbid flow (Harms *et al.*, 1982; Walker *et al.*, 1983; Nottvedt and Kreisa, 1987). The hummocky cross-stratification in sandstone beds of the Verkhovka Formation is likely a result of such an interaction. Small isolated gutter casts characteristic of deposits under consideration also suggest a considerable contribution of turbid flow activity to the sandy material transport.

The stratified sandstone package (Plate I, fig. 7) in the middle formation part is traceable over a distance of 40 km, from lower reaches of the Syuzma River to the Agma Creek (Fig. 2). Its peculiar features, such as abrupt lower boundaries of the beds with current-formed erosion marks, combination of multistoried cross-lamination with thin horizontal bedding, and gutter casts, imply that the beds were deposited from turbid flows under conditions of intense influx of terrigenous material. Measurements of cross-lamination suggest a unimodal distribution of paleocurrent directions from the northeast (230°, n = 10). This is consistent with the unimodal character of swing marks and with the trend of flute casts (245°, n = 12) and of the package itself. The planar bedding characteristic of thick sandstone members seems to be a result of sand discharge from relatively rapid flows. This is evident from current-formed parting lineation that represents a response of a sand bed to flow configurations arising during boundary-layer streaks, provided the long-term regime and relatively high constant rate of sediment transport. According to all these data, the sandstone beds are interpreted as fluviomarine deposits.

In the southeastern White Sea area, western boundaries of present-day distribution area of the fluviomarine deposits are erosional. In the east, these deposits, predominantly sandstones with diverse slump structures, form thick (6 to 15 m) wedges oriented across the main direction of paleocurrents (Grazhdankin and Bronnikov, 1997). By all appearances, the quick accumulation of sand caused a slight seafloor sloping that destabilized sediments. In the host sequence, sandstone beds with ripple cross-lamination are intercalated with members of interbedded siltstone and mudstone, and these rocks are interpreted as sediments deposited in a zone of wave agitation and current activity (Grazhdankin and Bronnikov, 1997). Lenticular beds of thin-bedded sandstone with erosional soles, which are also characteristic of this area and extend along the main direction of paleocurrents, likely represent casts of submarine channels.

Thus, the lower mesocycle of the Verkhovka Formation was formed in an offshore area in distributary-mouth bar setting, where a river flow interacted with rough sea. The thick sequence of fluviomarine deposits represents the delta mouth bar extending in direction of turbid flows. Slope deposits accumulated in prodelta settings of the mouth bar flanks. The flows episodically penetrated in these settings and locally scoured channels in the bottom, though in general they were of a low density. Decelerating in the prodelta settings, flows discharged the suspended material that was subsequently reworked by wave flows, which created the widespread cross-stratification.

The upper mesocycle of the Verkhovka Formation is composed of thin-interbedded siltstone and mudstone deposited under conditions of progressive sorting of bottom sediments by wave flows. This is evident from local erosion marks recorded in deposits (Plate I, fig. 4), from cross-lamination of siltstone interbeds (Plate I, fig. 5), and from sandstone intercalations with ripple cross-stratification, which enclose flat mudstone pebbles. According to these data, the siltstone-mudstone sequence (13 m thick) of the upper mesocycle represents distal deposits of prodelta indicative of a relative sea-level rise in the late Verkhovka time. The middle interval of fluviomarine deposits consequently corresponds to the lowest position of sea level in the Lyamtsa-Verkhovka succession (Fig. 4).

Depositional environment of the Zimnie Gory Formation. The formation lower boundary outlines, as is suggested, the gently sloping bottom relief of a submarine valley that was dozens of meters deep and dozens of kilometers wide (Fig. 3). Basal conglomerate infills erosional scours in underlying sediments and imply the erosional origin of the boundary.

Desiccation marks have not been observed in the studied formation sections. Basal conglomerates are overlain by mudstone deposited in relatively low energy conditions and bearing abundant algae phytoleims. Interbedded sandstone, siltstone, and mudstone occurring higher in the section can be attributed to estuarine sediments of the relatively shallow-water genesis based on their lithologic peculiarities and abundant plant detritus characteristic of the rocks.

The thick stratified package of thin-, planar-, and cross-bedded sandstones represents an important characteristic of the formation elucidating the depositional environment. In the northeast, these sandstone beds extend for a distance of 30 km between the Torozhma and Zimnie Gory sites. Distinct flute casts, multistoried cross-stratification (Plate II, fig. 4), and widespread syngenetic deformations, including deformed cross-stratification, imply fluviomarine origin of the rocks (Swift *et al.*, 1991). Cross stratification suggests paleocurrents from the northeast (210°, n = 9). Across the beds' strike, the composition and structure of sandstone member change. In the northwest (northern Zimnie Gory sections), sandstone beds pinch out, and the member is composed of thin-laminated siltstone strata (Plate I, fig. 6). The well-sorted material of the latter, interlayers with ripple cross-lamination, and broadly arcuate swing marks (Plate I, fig. 8) are indicative of sedimentation settings affected by storm hydrodynamics. According to all these data, the sandstone member is interpreted as deposits of the axial zone of a mouth bar.

The lateral facies succession of the Zimnie Gory Formation therefore reflects gradual progradation of an estuary-mouth bar sedimentation system. The system developed from an incipient submarine valley incised into underlying sediments (Fig. 4). Local erosion is also recorded at the top of estuarine deposits, but this level marks the abrupt transition from estuarine to fluviomarine sedimentation at an earlier stage of progradation. In the upper formation part, there is persistent member composed of fine-laminated mudstone grading into interbedded siltstone and mudstone with sandstone intercalations. These rocks imply that the mouth bar settings of the terminal Zimnie Gory phase suddenly turned into prodelta settings.

Depositional environment of the Erga Formation. Cyclothems in the lower formation part reveal a characteristic sedimentary succession that is important for understanding of their depositional environment. The basal beds and isolated gutter casts of cyclothems are composed of thin-bedded sandstone. They often enclose flat mudstone pebbles concentrated near soles with occasional erosion marks. Thin horizontal and graded bedding of the rocks suggests that they represent a discharge product of turbid flows (Grazhdankin and Ivantsov, 1996). A slight seafloor sloping in response to quick accumulation of sand triggered development of syngenetic slump deformations (Plate I, fig. 9), and the rocks can be accordingly regarded as deposits of distributary delta channels. The thick sandstone beds grade upward into interbedded sandstone, siltstone, and mudstone. The ripple cross-lamination and symmetrical ripple marks widespread in the interbedded member are indicative of sedimentation under influence of weak wave flows. The overlying member of interbedded siltstone and mudstone corresponds to strandplain storm deposits. Finally, the topmost member of cyclothems is composed of fine-laminated mudstone deposited in low energy conditions.

Gutter casts characteristic of proximal prodelta facies (Plate II, fig. 1) suggest a zone of strong bypassing turbid flows that scoured gutters in seafloor. The gutters became immediately cast by coarse sediment partially discharged from turbid flows, which became more buoyant, ascended as plumes leaving behind the gutter casts, and transported the rest of suspended material to more distal settings.

Distributary and overflow channels filled with sediments are widespread in the upper member of lower mesocycle. Their soles with deep erosion marks and sandstone with planar lamination deposited in deepest parts (Plate II, fig. 5) imply that the channels were scoured by strong flows. Some casts with two "waterways" on the sole (Plate II, fig. 5) are indicative of channel branching. Infilling of the channels proceeded under conditions of rippling migration in a unidirectional flow as evident from occurrence of multistoried cross-lamination. Ripple marks on boundary planes between cross-bedded packages often have their crests flattened that is an argument in favor of episodic breaks in terrigenous influx and cessation of flow activity. Spill-over ripple marks suggest oscillatory pattern in deceleration of wave activity and open shallow-water settings. Measurements of cross beds (230°, n = 15), as well as trends of gutter casts (240°, n = 21) and channels (250°, n = 22) indicate that the source of terrigenous material was situated in the northeast.

Interbedded sandstone, siltstone, and mudstone characterizing the rest of the formation accumulated in a flat shallow-water plain favorable for progressive sorting of sedimentary material by waves, as evident from widespread symmetrical ripple marks. Sandstone packages in this sequence exhibit planar lamination and current-formed parting lineation, and suggest acceleration and discharge of turbid flows in shoal settings. Judging from morphology of cross sets, the filling of distributary channel developed in the course of migration of underwater dunes under influence of a long-term unidirectional flow. When cross-bedded intervals grade upward into sandstone beds with planar lamination (Plate II, fig. 6), the transition can be explained by the flow acceleration and shoaling. The general red coloration of deposits and siderite concretions are indicative of brackish-water environments (Pirrus, 1992). Measurements of cross beds (240°, n = 5) and trends of current-formed parting lineation (215°, n = 8) suggest the flow direction from the northeast.

To summarize, the estuarine and mouth bar areas of sedimentation in the Zimnie Gory time evolved into marine prodelta settings of the Erga epochs. The cyclothems resemble cyclic stratification of deltaic, schlieren, and molasse formations and suggest the analogous sedimentological mechanism that was controlled by the prodelta itself. The further evolution was associated with gradual transformation of marine prodelta settings into those of a flat freshwater plain extending away from the shore. Freshwaters flooded the plain via the system of multiple distributary channels and interacted with seawater of the offshore zone. Depositional settings described above characterize altogether a delta plain, and sedimentary succession of the Erga Formation recorded the history of that delta plain progradation from the northeast (Fig. 4). According to characteristics presented above, the prodelta deposits at the base of the Erga Formation correspond to the highest sea-level stand in the Zimnie Gory-Erga succession (Fig. 4).

Genetic Interpretation

Compositional and structural features of the deposits described above has lead to the conclusion that the studied Vendian Complex is accumulated mostly in settings of the delta-front platforms, whereas the delta tracts proper were situated northeastward of the studied outcrops. This is evident from the unimodal distribution of paleocurrent directions that is established based on measurements of cross bedding and trends of gutter casts, channels, and other current-formed structural elements. In general, it was a basin with an active hydrodynamics as evident from sedimentary material transport throughout the southeastern White Sea area and wide distribution of cross- and ripple cross-lamination in the well-sorted deposits. The both types of lamination characterize a complex circulation system with energetic transverse and along-shore currents in the open, relatively shallow offshore zone. The genetic analysis of diverse lithologic types shows that clastic material was transported into basin by long-lasted unidirectional flows.

As is established, flooding events in large deltas are associated with development of turbid flows, many of which are quasistationary, running over dozens of hours (Normark and Piper, 1991; Myrow and Southard, 1996; Mulder *et al.*, 1998). Concentration of material suspended in these flows is sufficient for sediment traction over the basin floor. The turbid flow models and processes observable in deltas show that inertia driven plumes are able to scour the basin floor and to form deposits of the turbidite type (Mulder *et al.*, 1998). The driving force of these hyperpycnal plumes (Normark and Piper, 1991) is inertia of river flows running into basin during flooding events in response to seasonal atmospheric precipitations, or after a rapid thawing of show and glaciers (Syvitski and Farrow, 1983; Maizels, 1989; Russel and Knudsen, 1999). Based on these data, I would like to compare the turbid flows, which transported sandy material to Vendian depositional settings in the southeastern White Sea area, with the hyperpycnal currents associated with flood events.

Thus, the fluviomarine deposits of the offshore sandy shoal near river mouth can be regarded as submarine or basinal alluvium. Their bedding style is likely to be of the flood origin, and the deposits proper can be regarded as inundites. Even, gently sloping seafloor relief in the offshore zone and high inertia of flows facilitated progradation of flood deposits far away from the shore. Along the delta front and strandplain flanks, there were prodelta settings, where sediments accumulated under influence of interacting river stream and rough sea. Prodelta represented a submarine platform suitable for delta progradation, indicative of which are gutter casts of variable size formed under influence of hyperpycnal inertia-driven plumes related in origin to flood events, and the cast fills consequently represent inundites. Absence of terrestrial vegetation conditioned the distinct event stratification of Vendian Complex in the southeastern White Sea area, and sedimentation of that time resembled sedimentation in offshore zones of recent sea basins situated in arid and Arctic regions (Syvitski and Farrow, 1983; Maizels, 1989; Russel and Knudsen, 1999).

Characteristic of Vendian deposits is the shagreen under surface of siltstone and sandstone beds ranging in thickness from 1–2 mm to 0.5 m (Plate II, figs. 7 and 8). Being independent of the beds' genesis, the shagreen under surface is however untypical of gutter casts and sandstone beds with cross, planar, or hummocky stratification, which have been deposited in settings with most active hydrodynamics. On the other hand, soles of this kind are characteristic of beds exemplifying the prodelta settings. Small load casts (Plate II, fig. 7) and tensile-stress folding (Plate II, fig. 8) can be viewed on the shagreen soles incrusted sometimes with fine pyrite grains and distinguishable pyritized remains of algal filaments (Plate II, fig. 7). Being entangled in meshwork, the remains cover considerable areas of the soles and appear to be buried in situ. According to these observations, the shagreen soles may represent impressions of microbial films (Seilacher *et al.*, 1985; Gerdes *et al.*, 2000; Gehling, 2000). These films presumably protected bottom sediments from scouring, as the shagreen soles are lacking erosion marks.

CONCLUSION

In general, the Vendian Complex of the southeastern White Sea area corresponds to the regressive sedimentary succession deposited in the offshore zone near river mouth, when the deltaic distributary system gradually prograded from the northeast, away from the Kanin-Timan fold-and-thrust belt. The incipient formation stage of the succession was associated with a quick flood and origination of strandplain settings. Except for a thin gravelstone cover at the base of the Lyamtsa Formation, there are no other records indicative of that flood. Sediments characteristic of ingression events have not been established near the succession base. Accordingly, the lower Vendian boundary is of transgressive origin (Fig. 4).

The analyzed structure and depositional environments of Vendian sediments show that the main boundary in the succession corresponds to the surface between the Verkhovka and Zimnie Gory formations and has been associated with scour and fill of a submarine valley. This boundary separates the Lyamtsa-Verkhovka and Zimnie Gory-Erga subcomplexes, each representing a tract of sedimentary system (Fig. 4).

According to the facies architecture, the Lyamtsa-Verkhovka Subcomplex is divisible into three units that correspond principal phases of sedimentation. The thick basal progradational unit of sandy to clayey deposits records transition of strandplain environments (Lyamtsa Formation) into the mouth bar settings (lower part of the lower Verkhovka mesocycle). The overlying clayey-sandy unit of fluviomarine deposits (upper part of the aforementioned mesocycle), therefore, marks the phase of the low sea-level stand. The upper unit of the subcomplex is composed of sandy-clayey deposits of the prodelta settings (upper mesocycle of the Verkhovka Formation). The whole subcomplex can be regarded as the regressive-transgressive tract of the mouth bar sedimentary system (Fig. 4).

The sedimentary succession of the Zimnie Gory-Erga Subcomplex also includes three units. The basal sandy-clayey one is represented by estuarine and mouth-bar sediments (Zimnie Gory Formation), the fill of a submarine valley. Sandy-clayey cyclothems of the overlying unit accumulated in prodelta settings during the phase of a high sea-level stand (lower mesocycle of the Erga Formation). Finally, the thick uppermost unit is composed of clayey to sandy sediments of the delta plain (middle and upper mesocycles of the Erga Formation). As a whole, the subcomplex can be attributed to the transgressive-regressive tract of the delta plain sedimentary system (Fig. 4).

The boundary between the Verkhovka and Zimnie Gory formations is lacking evidence for subaerial exposure. It is hardly admissible, therefore, that the submarine valley was scoured in response to a sea-level drop by the end of the Verkhovka time. Immediately below the erosion surface, there are distal prodelta deposits of the upper Verkhovka mesocycle, and this is as well inconsistent with the area emergence at that time. There are two possible explanations for scouring at the base of the Zimnie Gory Formation: it could be a result of the nearshore slope erosion during a quick transgression, or a consequence of the offshore marine erosion in response to decline of terrestrial influx (Swift *et al.*, 1987; Galloway, 1989). The boundary separates two sedimentary system tracts and likely can be defined as the sequence boundary (Fig. 4).

In addition to this boundary, there are two transgressive boundaries distinguishable in the Vendian succession (Fig. 4). The lower one is conformable, and it originated in response to the northeastward shift of depositional system. This boundary separates the siltstone-mudstone sequence with sandstone interbeds of wave-agitation zone (Lyamtsa Formation) from overlying thin-bedded mudstone (Verkhovka Formation) deposited in relatively quiet waters (Fig. 4). Deposits of the Verkhovka Formation have accumulated in the course of gradual progradation of the mouth bar under hydrodynamic conditions, which were more active than hydrodynamics of the strandplain progradation during the accumulation epoch of the Lyamtsa Formation.

Moreover, the early diagenetic concretions widespread in lower beds of the Verkhovka Formation represent a characteristic feature of the important marker horizon traceable along the northeastern margin of the East European platform to the western flank of the Urals (Kirsanov, 1968). The concretions marking a regional event were probably formed in sediments at the time of low sea-level stand and maximum progradation of the mouth bar. Thus, the boundary between Lyamtsa and Verkhovka formations divides two depositional systems (those of strandplain and mouth bar) within the sedimentary system tract. As corresponding to the beginning of the new sedimentary megacycle, it can be regarded as the subsequence boundary (Fig. 4).

The upper transgressive boundary is between the Zimnie Gory and Erga Formations. The regressive mesocycles underneath change into transgressive ones above this boundary suggesting a sharp break in the sedimentary system evolution (Fig. 4). The boundary separates the estuarine and mouth bar sediments (the submarine valley fill) from overlying prodelta sediments deposited under conditions of the high sea-level stand. Deep (1 to 5 m) incisions in underlying deposits, which are characteristic of this boundary, are filled with fine-grained sandstone enclosing pebbles. These pebbles are in imbricated position within fine-grained sandstone matrix. Their drag marks and high frequency of gutter casts at the interface are indicative of the recurrent intense wave agitation and condensed sedimentation. It is likely that transgression exhumed the fluvial pebbly accumulations and redistributed pebbles in a form of lenticular intercalations. Thus, the lower boundary of the Erga Formation corresponds to the maximum flood event and divides two depositional systems (those of mouth bar and prodelta) within the sedimentary system tract. As marking simultaneously the commencement of the new sedimentary megacycle, it can be viewed as the subsequence boundary (Fig. 4).

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REFERENCES

Aksenov, E.M., *Vend Vostochno-Evropeiskoi platformy* (The Vendian of East European Platform), Sokolov, B.S. and Fedonkin, M.A., Eds., Moscow: Nauka, 1985, pp. 3–34.

Aksenov, E.M. and Igolkina, N.S., On Distinguishing the Redkino Formation in the Valdai Group in the Northern Russian Platform, *Izv. Vyssh. Uchebn. Zaved., Geol. Razved.*, 1969, no. 8, pp. 22–25.

Aksenov, E.M. and Volkova, S.A., Volcanogenic–Sedimentary Horizons in the Redkino Formation of the Valdai Group, *Dokl. Akad. Nauk SSSR*, 1969, vol. 188, no. 3, pp. 635–638.

Aksenov, E.M., Keller, B.M., Sokolov, B.S., *et al.*, General Stratigraphic Scheme for the Upper Precambrian of the Russian Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1978, no. 12, pp. 17–34.

Allen, P.A., Hummocky Cross-Stratification Is Not Produced Purely under Progressive Gravity Waves, *Nature* (London), 1985, vol. 313, pp. 562–564.

Coleman, J.M., Roberts, H.H., Murray, S.P., and Salama, M., Morphology and Dynamic Sedimentology of the Eastern Nile Delta Shelf, *Mar. Geol.*, 1981, vol. 42, pp. 301–326.

Verkhnii dokembrii Evropeiskogo Severa SSSR (Ob"yasnitel'naya zapiska k scheme stratigrafii (Upper Precambrian in the North European Part of the USSR: Explanatory Notes to Stratigraphic Scheme), Dedeev, V.A. and Keller, B.M., Eds., Syktyvkar: AN SSSR, 1986.

Fedonkin, M.A., *Belomorskaya biota venda (dokembriiskaya besskeletnaya fauna severa Russkoi platformy)* (Vendian Biota of the White Sea Region: Precambrian Fauna Lacking Skeleton from the Northern Russian Platform), Moscow: Nauka, 1981.

Fedonkin, M.A., Systematic Description of Vendian Metazoa, *Vendskaya sistema. Istoriko-geologicheskoe i paleontologicheskoe obosnovanie, T. 1: Paleontologiya* (Vendian System, Geological and Paleontological Substantiation, Vol. 1: Paleontology), Sokolov, B.S. and Ivanovskii, A.B., Eds., Moscow: Nauka, 1985, pp. 70–106.

Galloway, W.E., Genetic Stratigraphic Sequences in Basin Analysis I: Architecture and Genesis of Flooding-Surface Bounded Depositional Units, *Bull. Am. Assoc. Petrol. Geol.*, 1989, vol. 73, no. 2, pp. 125–142.

Gehling, J.G., Environmental Interpretation and a Sequence Stratigraphic Framework for the Terminal Proterozoic Ediacara Member within the Rawnsley Quartzite, South Australia, *Precambrian Res.*, 2000, vol. 100, pp. 65–95.

Gerdes, G., Klenke, T., and Noffke, N., Microbial Signatures in Peritidal Siliciclastic Sediments: A Catalogue, *Sedimentology*, 2000, vol. 47, pp. 279–308.

Gnilovskaya, M.B., New Vendian Saarinids from the Russian Platform, *Dokl. Ross. Akad. Nauk*, 1996, vol. 348, no. 1, pp. 89–93.

Gnilovskaya, M.B., Veis, A.F., Bekkker, Yu.R., *et al.*, Pre-Ediacarian Fauna from Timan (Annelidomorphs of the Late Riphean), *Stratigr. Geol. Korrelyatsiya*, 2000, vol. 8, no. 4, pp. 11–39.

Grazhdankin, D.V., The Ediacaran Genus *Inaria*: A Taphonomic/Morphodynamic analysis, *Neues Jahrb. Geol. Palaont. Abh.*, 2000, vol. 216, no. 1, pp. 1–34.

Grazhdankin, D.V. and Bronnikov, A.A., New Locality of Late Vendian Remains of Jellyfish-Type Organisms in the Onega Peninsula, *Dokl. Ross. Akad. Nauk*, 1997, vol. 357, no. 6, pp. 792–796.

Grazhdankin, D.V. and Ivantsov, A.Yu., Reconstruction of Biotopes of Ancient Metazoa of the Late Vendian White Sea Biota, *Paleontol. J*, 1996, vol. 30, no. 6, pp. 676–680.

Harms, J.C., Southard, J.B., and Walker, R.G., *Structures and Sequences in Clastic Rocks*, Calgary: SEPM, 1982.

Holmes, C.W., Geochemical Indices of Fine Sediment Transport, Northwest Gulf of Mexico, *J. Sediment. Petrol.*, 1982, vol. 52, pp. 307–321.

Igolkina, N.S., Age of Sandy-Clayey Deposits at the “Zimnii Coast” of the White Sea, *Materialy po geologii Evropeiskoi territorii SSSR* Leningrad: Vses. Geol. Inst, 1956, no. 14, pp. 169–173.

Igolkina, N.S., A Possibility to Distinguish the Baltic Complex in the Northern Russian Platform, *Geologiya Evropeiskoi territorii SSSR* (Geology of the USSR European Territory), Leningrad: Vses. Geol. Inst., 1959, pp. 17–23.

Ivantsov, A.Yu., A New Dickinsoniid Representative from Upper Vendian, The Zimnii Coast Locality at the White Sea (Russia, Arkhangelsk Oblast), *Paleontol. Zh.*, 1999, no. 3, pp. 3–11.

Ivantsov, A.Yu., *Vendia* and Other Precambrian “Arthropods,” *Paleontol. Zh.*, 2001, no. 4, pp. 3–10.

Kalberg, E.A., *Geologicheskoe opisanie Onezhskogo poluostrova* (Geological description of the Onega Peninsula), Leningrad: Gostoptekhizdat, 1940.

Kirsanov, V.V., To the Problem of Stratigraphy and Correlation of Vendian Deposits in the Russian Platform Eastern Margin, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1968, no. 6, pp. 86–103.

Krivtsov, A.I., New Data on the Lower Paleozoic, the Eastern Flank of Baltic Shield, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1958, no. 4, pp. 63–75.

Kuz’menko, Yu.T. and Burzin, M.B., *Stratigraficheskaya skhema vendskikh otlozhenii Moskovskoi sineklizy. Ob”yasnitel’naya zapiska* (Stratigraphic Scheme for Vendian Deposits of the Moscow Syneclise, Explanatory Notes), Moscow: RMSK, 1996.

Maizels, J.K., Sedimentology, Paleoflow Dynamics and Flood History of Jokulhlaup Deposits: Paleohydrology of Holocene Sediment Sequences in Southern Iceland Sandur Deposits, *J. Sediment. Petrol.*, 1989, vol. 59, pp. 204–223.

Martin, M.W., Grazhdankin, D.V., Bowring, S.A., *et al.*, Age of Neoproterozoic Bilaterian Body and Trace Fossils, White Sea, Russia: Implications for Metazoan Evolution, *Science*, vol. 288, pp. 841–845.

Molin, V.A., Budanov, G.F., Koloda, N.A., and Plotnikov, M.A., *Permskie krasnotsvetnye formatsii severa Russkoi plity* (Permian Red-Bed Formations in the North Russian Plate), Leningrad: Nauka, 1986.

Mulder, T., Syvitski, J.P.M., and Skene, K.I., Modeling of Erosion and Deposition by Turbidity Currents Generated at River Mouths, *J. Sediment. Res.*, 1998, vol. 68, no. 1, pp. 124–137.

Myrow, P.M. and Southard, J.B., Tempestite Deposition, *J. Sediment. Res.*, 1996, vol. 66, no. 5, pp. 875–887.

Normark, W.R. and Piper, D.J.W., *Initiation Processes and Flow Evolution of Turbidity Currents: Implications for the Depositional Record*, Osborne, R.H., Ed., Tulsa: SEPM, 1991, pp. 207–230.

Nottvedt, A. and Kreisa, R.D., Model for the Combined-Flow Origin of Hummocky Cross-Stratification, *Geology*, 1987, vol. 15, pp. 357–361.

Oertel, G.F. and Dunstan, W.M., Suspended-Sediment Distribution and Certain Aspects of Phytoplankton Production Off Georgia, U.S.A., *Mar. Geol.*, 1981, vol. 40, pp. 171–197.

Pirrus, E.A., Freshening of the Late Vendian Basin on the East European Craton, *Proc. Estonian Acad. Sci., Geol.*, 1992, vol. 41, no, 3, pp. 115–123.

Popov, L. and Gorjansky, V., First Record of Upper Cambrian from the Eastern White Sea Coast: New Evidence from Obolids (Brachiopoda), *GFF*, 1994, vol. 116, pp. 31–35.

Ragozina, A.L. and Sivertseva, I.A., *Mikrofossilii valdaiskoi serii severo-zapada Arkhangel’skoi oblasti* (Microfossils of the Valdai Group from the Northwestern Arkhangelsk Oblast), Sokolov, B.S. and Ivanovskii, A.B., Eds., Moscow: Nauka, 1985, pp. 139–144.

Russell, A.J. and Knudsen, Ó., Controls on the Sedimentology of the November 1996 Jökulhlsup Deposits, Skeiðarásandur, Iceland, *Fluvial Sedimentology IV*, Smith, N.D. and Rogers, J., Eds., Oxford: Blackwell, 1999, pp. 315–329.

Sahl, L.E., Merrell, W.J., McGrail, D.W., and Webb, J.A., Transport of Mud on Continental Shelves: Evidence From the Texas Shelf, *Mar. Geol.*, 1987, vol. 76, pp. 33–43.

Seilacher, A., Reif, W.-E., and Westphal, F., Sedimentological, Ecological and Temporal Patterns of Fossil Lagerstätten, *Phil. Trans. R. Soc.* (London), 1985, vol. 311, pp. 5–23.

Sivertseva, I.A. and Stankovsky, A.F., New data on Geology of Upper Vendian Deposists in the Northwestern Arkhangelsk Oblast, *Vestn. Leningr. Univ.*, 1982, no. 12, pp. 30–40.

Sokolov, B.S., On the Age of Oldest Sedimentary Cover of the Russian Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952, no. 5, pp. 21–31.

Solontsov, L.F. and Aksenov, E.M., On the Valdai Group Stratigraphy in the East European Platform, *Izv. Vyssh. Uchebn. Zaved., Geol. Razved.*, 1970, no. 6, pp. 3–13.

Solontsov, L.F., Aksenov, E.M., Andreev, S.P., and Polikarpova, N.T., To Lithology and Indexation of Sandstone-Siltstone Members and Beds of the Valdai Group in Moscow Syneclise, *Tr. Geol. Inst.* (Kazan), 1970, no. 30, pp. 324–345.

Stankovsky, A.F., Sinitsin, A.V., and Shinkarev, N.F., Buried Traps of the Onega peninsula, White Sea Region, *Vestn. Leningr. Univ.*, 1972, no. 18, pp. 12–20.

Stankovsky, A.F., Verichev, E.M., Grib, V.P., and Dobeiko, I.P., The Vendian of Southeastern White Sea Region, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1981, no. 2, pp. 78–87.

Stankovsky, A.F., Verichev, E.M., and Dobeiko, I.P., The Vendian of Southeastern White Sea region, *Vendskaya sistema. Istoriko-geologicheskoe i paleontologicheskoe obosnovanie, T. 1: Paleontologiya* (Vendian System, Geological and Paleontological Substantiation, Vol. 2: Stratigraphy and Geological Processes), Sokolov, B.S. and Fedonkin, M.A., Eds., Moscow: Nauka, 1985, pp. 67–76.

Swift, D.J.P., Hudelson, P.M., Brenner, R.L., and Thompson, P., Shelf Construction in a Foreland Basin: Storm Beds, Shelf Sandbodies, and Shelf-Slope Depositional Sequences in the Upper Cretaceous Mesaverde Group, Book Cliffs, Utah, *Sedimentology*, 1987, vol. 34, pp. 423–457.

Swift, D.J.P., Phillips, S., and Thorne, J.A., Sedimentation on Continental Margins, IV: Lithofacies and Depositional Systems, *Shelf sand and Sandstone Bodies: Geometry, Facies, and Sequence Stratigraphy* Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., Eds., Oxford: Blackwell, 1991, pp. 89–152.

Syvitski, J.P.M. and Farrow, G.E., Structures and Processes in Bayhead Deltas, Knight and Bute Inlets, British Columbia, *Sediment. Geol.*, 1983, vol. 36, pp. 217–244.

Walker, R.G., Duke, W.L., and Leckie, D.A., Hummocky Stratification: Significance of Its Variable Bedding Sequences: Discussion, *Bull. Geol. Soc. Am.*, 1983, vol. 94, pp. 1245–1251.

Wright, L.D. and Coleman, J.M., Mississippi River Mouth Processes: Effluent Dynamics and Morphologic Development, *J. Geol.*, 1974, vol. 82, pp. 751–778.

Yakobson, K.E., Kuznetsova, M.Yu., Stankovsky, A.F., *et al.*, The Riphean at Zimnii Coast of the White Sea, *Sov. Geol.*, 1991, no. 11, pp. 44–48.

Zekkel’, Ya.D., *Geologicheskie issledovaniya v raione Zimnego berega Belogo morya, basseine Kuloya i nizov’ev Mezeni* (Geological Investigations in the Zimnii Coast Area of the White Sea, Kuloi River Basin, and in Lower Reaches of the Mezen River), Arkhangelsk: Sev. Geol. Upravl., 1939.

Zoricheva, A.I., The Northern Russian Platform, *Geologiya SSSR, T. 2. Arkhangel’skaya, Vologodskaya oblastu i Komi ASSR* (Geology of the USSR, Vol. 2: Arkhangelsk to Vologda Oblast and Komi ASSR), Zoricheva, A.I., Ed., Moscow: Gosnauchtekhizdat, 1963, pp. 79–99.