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Paleoclimatic Environments of the Formation of Upper Vendian Rocks on the Belomorian–Kuloi Plateau, Southeastern White Sea Region

D. V. Grazhdankin[1], V. N. Podkovyrov[2], and A. V. Maslov[3]
[1]Paleontological Institute, Russian Academy of Sciences,
Profsoyuznaya ul. 123, Moscow, 117768 Russia
e-mail: dgra99@esc.cam.ac.uk
[2]Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences,
nab. Makarova 2, St. Petersburg, 197034 Russia
e-mail: vpodk@mail.ru
[3]Zavaritsky Institute of Geology and Geochemistry, Ural Division, Russian Academy of Sciences,
Pochtovyi per. 7, Yekaterinburg, 620151 Russia
e-mail: maslov@igg.uran.ru

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Abstract—Reconstruction of Vendian climatic conditions on the East European Craton is of principle importance for elucidation of the Ediacarian biota habitat. However, paleogeographic reconstructions for this time are largely based on fragmentary and controversial paleomagnetic data. The degree of rock maturity deduced from lithochemical indicators allowed us to identify two stages of Late Vendian sedimentation on the Belomorian–Kuloi Plateau. The first (Lyamitsa–Verkhov) stage was characterized by the delivery of immature clastic material to the basin from a provenance with arid climate. The second (Erga–Padun) stage was marked by the input of relatively mature aluminosilicate clastics from a provenance with mild humid climate. The sedimentation stages approximately coincide with replacement of the shallow-water marine environment by the fluvioalluvial environment marked by steady and intense perennial river drainage from a highland in the northeast. In the Late Vendian (since 555 Ma ago), the northeastern area of the East European Craton was influenced by humid climate.

INTRODUCTION

Neoproterozoic sedimentary rocks bear information on the global reorganization of geo- and biosphere caused by radiation of Metazoa and successive installation of a pyramid of complex biocoenotic links in a rapidly evolving ecosystem. Based on Neoproterozoic sections of the East European Craton, the Upper Vendian succession has been subdivided into three horizons that correspond to the main evolutional stages: the Redkino Horizon with fossils of the Ediacarian-type biota, the Kotlin Horizon characterized by the abundance of algal phytoleims, and the Rovno Horizon with various fossil traces at its base (*Vendskaya* …, 1985). There are grounds to suggest that the cascade of Late Vendian innovations resulted in global perturbations in the arrangement of biogeochemical cycles at the Proterozoic–Paleozoic boundary: phosphogenesis, deposition of carbonaceous shales, changes in the character of sedimentation and geochemistry of diagenesis, and global variations in the ratios of carbon and strontium isotopes (Shenfil, 1983; Magaritz *et al.*, 1991; Knoll and Walter, 1992; Brasier, 1992; Tucker, 1992; Brasier *et al.*, 1994; Logan *et al.*, 1995).

However, incomplete knowledge of relationships between biotic and abiotic factors hampers the refinement of consecutive Neoproterozoic events on the East European Craton. First results of the study of coordinated changes in fossil assemblages and sedimentation environments on the East European Craton have shown that the Late Vendian marine benthic communities were characterized by a narrow ecological specialization and high sensitivity to environment (Burzin, 1996; Fedonkin, 1996; Grazhdankin, 2004). The next step must be related to investigation of the role of climatic and other abiotic factors in the systematic change of biotic phenomena.

Efforts to reconstruct paleoclimatic environments were repeatedly undertaken during the study of Upper Vendian sedimentary rocks in basins of the Moscow and Mezen syneclises. Based on the analysis of terrigenous clay minerals, Pirrus (1980) showed that the provenances were unstable in the Late Vendian. He believed that the most weathered material was delivered from a vast poorly dissected humid land in the western area of the basins mentioned above, while the least weathered clastics were derived from arid highlands in the north.

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The red color of the upper part of the section is interpreted as an indication of replacement of the warm humid climate by the arid tropical climate (Aksenov, 1985) or freshening of the basin under conditions of the severe cold paleoclimate (Pirrus, 1992). However, these interpretations are not supported by data on trace elements and composition of authigenic clayey components that testify to a significant upsection augmentation of the role of chemical weathering under conditions of warm humid paleoclimate (Petrovskaya *et al.*, 1972; Bessonova *et al.*, 1980).

In the present communication, we used lithochemical indicators to estimate the degree of clastic material maturity. The lithological–sedimentological analysis provided insights into mechanisms of the transport of aluminosilicate clastic material to the northeastern part of the Mezen Syneclise in the Late Vendian. The study is based on the lithochemical data with the consideration of lithological–sedimentological indicators for the Belomorian–Kuloi Plateau in the southeastern White Sea region. We examined the cores from boreholes 770 (Chidviya) and 772 (Upper Kepina) drilled in the 1980s at headwaters of the Zimnyaya Zolotitsa River (Expedition no. 17 of the Nevskgeologiya Industrial-Geological Association). The cores were described by V.V. Tretyachenko (unpublished report, 1994; Severgeolkom Territorial Geological Repository). We also used the whole-rock chemical compositions of sandstones and mudstones taken from the database of chemical analyses of Precambrian sedimentary rocks (PRECSED) compiled by the Institute of Precambrian Geology and Geochronology, St. Petersburg. The sampling was carried out by A.V. Sochava, D.V. Borchwardt, and M.B. Gnilovskaya.

VENDIAN LITHOSTRATIGRAPHY OF THE BELOMORIAN–KULOI PLATEAU

The Belomorian–Kuloi Plateau is situated on the northwestern slope of the Mezen Syneclise of the East European Craton (Fig. 1). The Mezen Syneclise also includes the Leshukon and Timan troughs and the Koinas Arch. The Mezen Syneclise passes into the Baltic Monocline (western slope of the Baltic Shield) on the northwest, west, and southwest; it borders with the Moscow Syneclise on the south via the Luza Saddle; passes into the Upper Kama Basin (Volga–Ural region) on the southeast; and joins the Kanin–Timan foldthrust belt along the deep-rooted West Timan Fault on the east and north (*Verkhnii* ..., 1986; *Stratigraficheskaya* ..., 1996, 2000; Olovyanishnikov, 1998).

The Upper Vendian tuffaceous–terrigenous sequence occurs at the base of sedimentary cover on the northwestern slope of the Mezen Syneclise as a regression series of coastal-marine, fluviomarine, and alluvial sediments with a total thickness of 1000 m. The deep structure of Vendian rocks in the Belomorian–Kuloi Plateau was first studied in the late 1980s during the geological survey under the supervision of A.F. Stankovskii. Stankovskii *et al.* (1981) correlated the lower part of the section with the Ust'-Pinega Formation of the Onega Peninsula, while the upper part was correlated with the Lyubim and Reshma formations of the Moscow Syneclise. Furthermore, based on the predominant color and petrography of rocks, they subdivided the Ust'-Pinega Formation into the Tamitsa, Lyamitsa, Arkhangel'sk, Verkhov, Syuz'ma, Vaizitsa, and Zimnegorsk Beds.

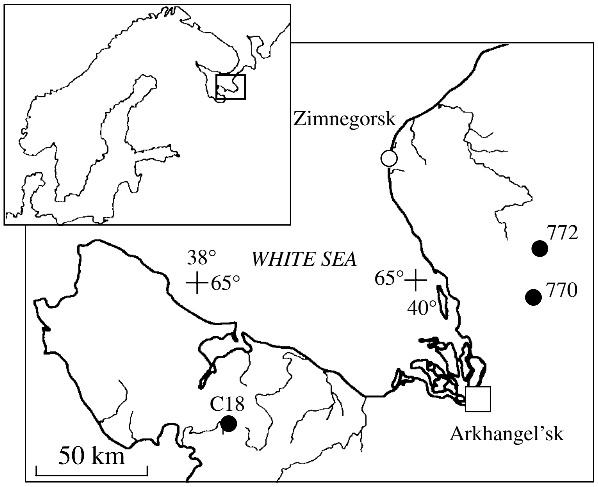

Fig. 1. Index map of studied boreholes and outcrops in the Zimnegorsk area.

In a similar way, the Lyubim Formation was subdivided into the Erga and Mel'sk Beds; the Reshma Formation, into the Zolotitsa and Tovsk Beds (Stankovskii *et al.*, 1981, 1985). These beds have widely been cited in the literature and used in applied geology. They have been regarded as subformations in some recent stratigraphic schemes. At the extended meeting of the Interdepartmental Stratigraphic Committee held in Syktyvkar (1983), the Lyubim and Reshma formations were replaced by the Mezen and Padun formations, respectively, without specifying their stratotypes (*Verkhnii* ..., 1986).

At present, we are carrying out a revision of the regional stratigraphy of the Vendian sequence in the southeastern White Sea region (Grazhdankin, 2003) because of the following reasons. First, the discovery of volcanic ash interlayers in the Vaizitsa Beds in the Zimnegorsk section (Martin *et al.*, 2000) made it possible to refine the volume of the Zimnegorsk Bed. Second, the scrutinization of Vendian successions in the Verkhov and Solza river valleys on the Onega Peninsula (Grazhdankin and Bronnikov, 1997) revealed a greater volume of the Syuz'ma Beds, which turned out to be exposed in the Zimnie Gory area as well. The western boundary of the area occupied by the Mezen Formation on the Onega Peninsula has also been revised. Third, mapping of formation boundaries in outcrops in the Zimnie Gory area and along the Torozhma River revealed that the lenticular shape of the Vaizitsa, Zimnegorsk, and Erga Beds is related to the filling of a series of incised valleys, rather than the erosion of rocks prior to the Kotlin time (Stankovskii *et al.*, 1985). This discovery made it possible to solve controversies in the correlation of boreholes on the Belomorian–Kuloi Plateau. Results of the lithogenetic study promoted the identification of lithotype associations, cyclic internal structure of sequences, and distribution of facies. Based on the data obtained, we proposed a new stratigraphic scheme of Vendian sedimentary rocks for the southeastern White Sea region. In this classification, the Ust'-Pinega Formation is replaced by the Lyamitsa, Verkhov, and Zimnegorsk formations; the Mezen Formation, by the Erga Formation (Grazhdankin, 2003). The Padun Formation is conditionally included in the Upper Vendian succession (Stankovskii *et al.*, 1981, 1985; Grazhdankin, 2003).

The Tamitsa Beds were traditionally regarded as a basal unit of the Ust'-Pinega Formation (Stankovskii *et al.*, 1981, 1985). However, some researchers correlate these beds with the Pletenevo Formation in the Moscow Syneclise (this point of view was reflected in the stratigraphic scheme approved in Syktyvkar). These rocks are not exposed in the southeastern White Sea region. Therefore, they were studied only in borehole sections (poorly sorted variegated quartz sandstones and packets of gravelstones with kaolinite cement). The Tamitsa sandstones and gravelstones are characterized by parallel and unilateral cross-bedding.

Owing to the close spacing of boreholes drilled on the Onega Peninsula, we managed to establish that the gravelstone and conglomerate packets are confined to the southern wall of the Onega Graben. In axial zone of the graben, they wedge out within the sandstones, which are indistinguishable in structure from underlying rocks of the Upper Riphean Nenoksa Formation. Therefore, the Tamitsa Beds have been eliminated from the Upper Vendian succession (Grazhdankin, 2003).

The Lyamitsa and Verkhov formations are composed of cyclic alternation of thin-bedded clays with intercalations of fine-grained sandstones and clays. The cyclites are shoaling upsection successions of beds. The base of each cyclite coincides with the submergence surface, which is traceable in boreholes for tens of kilometers. Therefore, the cyclites may be regarded as parasequences (Grazhdankin, 2003). The base of each parasequence is composed of transgressive thin-bedded clays overlain by intercalating clays and siltstones with carbonate interlayers that correspond to the transgression peak. The cyclite is crowned with a regressive member of intercalating siltstones and clays with interlayers of storm sandstones. Thin interlayers of volcanic ash occur at the base of the Lyamitsa and Verkhov formations within the thickest intervals of thin-bedded clays (Lyamnitsa and Verkhov Beds in Stankovskii's scheme). In the middle of the Verkhov Formation, the regressive section of one parasequence includes a packet of fluviomarine sandstones with lenticular shape of beds that fills diverse channel casts (Syuz'ma Beds in Stankovskii's scheme). This packet corresponds to the lowest sealevel stand during the Lyamitsa–Verkhov sequence accumulation (Grazhdankin, 2003). The thickness of the Lyamnitsa Formation attains 200 m, while the Verkhov Formation is more than 130 m thick (probably, as much as 200 m).

The base of the Zimnegorsk Formation is marked by an erosional unconformity with the topographic gradient locally reaching 180 m (system of incised valleys). The representative section of such valleys studied in outcrops of the Belomorian–Kuloi Plateau (Zimnie Gory and Torozhma River) is composed of the following units (from bottom to top): lenticular conglomerate interlayers (0.1–0.2 m); thick packet of mature quartz sandstones with lenticular bedding (up to 4 m); thick packet of chocolate brown thin-bedded clay (10 m in Zimnie Gory) with interlayers of volcanic ash (Vaizitsa Beds in the Stankovskii's scheme); and intercalating sandstones, siltstones, and clays (Zimnegorsk Beds up to 150 m thick). Fine- and medium-grained fluviomarine sandstones fill casts of scours and channels. They are characterized by multistage cross- or parallel-bedding. The Zimnegorsk Formation is irregularly developed and confined to incised valleys (Grazhdankin, 2003). The thickness of this formation in the Torozhma Borehole is 180 m.

Scours and incised valleys with a height difference of up to 25 m are observed at the roof of the Zimnegorsk Succession. The valleys are filled with basal sediments of the Erga Formation (Erga Beds in Stankovskii's scheme). These sediments show a distinct cyclic pattern and include several transgressive microcyclites 1.3–3.2 m thick. Thin-bedded yellowish gray sandstones (0.5–0.6 m) with diverse submarine slump deformations occur at the base of the microcyclites. Signs of erosion at the base of some layers, coupled with thin horizontal and graded bedding, indicate that the sandy material was deposited by turbid currents. Hence, these sediments may be regarded as discharges of deltaic aprons. The thick sandstone beds gradually give way to a packet (0.4–0.7 m) of intercalating sandstones, siltstones, and clays characterized by oblique cross-bedding and symmetric ripple marks, indicating their formation in the zone of weak waves and currents.

The sandy sediments are overlain by intercalating greenish gray siltstones and clays (alluvial plain sediments). The microcyclites are crowned with members of gray thin-bedded clays formed under quiet hydrodynamic conditions. Thus, the filling of incised valleys at the base of the Erga Formation may be interpreted as a series of swash deltas (dominated by marine agitation) with a well-developed prodelta front. In localities unaffected by the incision of valleys, the basal sediments of the Erga Formation are composed of mature quartz sandstones up to 2 m thick.

The remaining part of the Erga Formation consists of sandstones, siltstones, and clays related to the channel and interchannel facies of the deltaic distributive system. The cross-bedded variegated sandstones contain siderite nodules. The siltstones are also variegated (violet, bright brown, yellow, and orange in color). The mudstones are brown and locally dark gray. Stankovskii identified these rocks as the Mel'sk Beds. The thickness of the Erga Formation in boreholes reaches 200 m (Grazhdankin and Bronnikov, 1997).

According to the modern stratigraphic scheme of the southeastern White Sea region, the Upper Vendian succession is crowned with the Padun Formation, the structure and sedimentation environment of which remain virtually unstudied. Sections of this formation have been described in detail only along the Zimnyaya Zolotitsa River, where one can see outcrops of the lowermost part of the section and the erosional contact with the underlying Erga Formation. However, the thickness of the Padun Formation probably exceeds 250 m in boreholes drilled on the Belomorian–Kuloi Plateau (Stankovskii *et al.*, 1985; Grazhdankin and Bronnikov, 1997). In the studied area, the Padun Formation consists of intercalations of medium- and coarse-grained sandstones with a minor siltstone. Clays are atypical. The red-brown poorly cemented sandstones are characterized by parallel or multistage cross-bedding (the thickness of separate series is more than 1 m) and interpreted as fluvial channel sediments. Small clay pebbles are observed on the bedding surface of cross-laminas. Numerous overturned intraformational folds with deformed cross-lamina series can be seen in sandstones.

The U–Pb age of zircon from an ash interlayer, 12 mm thick, located 0.5 m above the base of the Verkhov Formation in an outcrop along the Agma Creek on the Onega Peninsula near Borehole S18 (Agma) was 558 ± 1 Ma. The ash interlayer (0.1 m) located 2 m above the base of the Zimnegorsk Formation in an outcrop near the Medvezhii Creek mouth in Zimnie Gory yielded 555.3 ± 0.3 Ma (Martin *et al.,* 2000; Grazhdankin, 2003).

We take into consideration the alternative subdivision of Upper Vendian sequences in the Mezen Syneclise based on the reinterpretation of results obtained by exploration geophysics using the cyclic approach (Burzin and Kuz'menko, 2000). In this scheme, the lower boundaries of stratigraphic units are drawn along the base of sandstone units that are prominent in borehole sections with a low core recovery. Such sections show a succession of transgressive cyclites that are inconsistent with the pattern observed in outcrops (Grazhdankin and Bronnikov, 1997; Grazhdankin, 2003).

SUBDIVISION OF SECTIONS IN BOREHOLES 770 AND 772

The lower boundary of Upper Vendian rocks in Borehole 770 is drawn at a depth of 885 m at the base of the 18-m-thick member composed of variegated (greenish gray and chocolate brown) thin-bedded clays with interlayers of volcanic ash (Fig. 2).

The underlying red-colored micaceous feldspar–quartz sandstones make up the Chidviya Formation 536 m thick (Yakobson *et al.*, 1991). V.V. Tretyachenko studied the borehole section and correlated brown feldspar–quartz sandstones from the interval of 860–855 m with the Tamitsa Beds of the Ust'-Pinega Formation (Upper Vendian). However, these sandstones do not differ in composition, structure, and texture from underlying rocks of the Chidviya Formation. Therefore, they are excluded from the Upper Vendian succession in the present communication. The Quaternary loam rests upon the Vendian rocks at a depth of 44 m with signs of erosion at the base.

The Upper Vendian succession in Borehole 770 (44–855 m) is subdivided into the Lyamitsa, Verkhov, Erga, and Padun formations. It should be noted that two members of chocolate brown thin-bedded clays from the interval of 652–546 m contain volcanic ash interlayers at 606–546 and 652–631 m (Fig. 2). The Verkhov Formation reveals a similar structure in outcrops and boreholes on the Onega Peninsula (Grazhdankin, 2003). Therefore, one can confidently correlate this interval with the base of the Verkhov Formation. Tretyachenko correlated the upper clay member (606–546 m) with the Vaizitsa Beds and the intermediate unit of intercalating sandstones, siltstones, and clays (Fig. 2, 631–606 m) with the Syuz'ma Beds. We believe that such variant of subdivision and correlation of rocks in Borehole 770 is less reliable.

We did not identify the Zimnegorsk Formation in Borehole 770, probably, because this area was not affected by incision of valleys before the Zimnegorsk epoch. Tretyachenko correlated the interval of 546–406 m in Borehole 770 with the Zimnegorsk Beds. This could be related to the erroneous correlation of the underlying chocolate brown clay unit with the Vaizitsa Beds. It has been established that the thickness of the Zimnegorsk Formation on the Belomorian–Kuloi Plateau gradually diminishes from 180 m in Borehole Torozhma to 60 m in the Zimnegorsk section. This formation is missing in the southern sections of boreholes Labino, Patrakeevka, and Arkhangel'sk (this conclusion is consistent with Stankovskii's opinion). Borehole 770 is located in the same area. Therefore, it is hardly probable that rocks of the Zimnegorsk Formation are locally developed here, and they can attain 200 m in thickness. We suggest that the Erga Formation in Borehole 770 directly overlaps the Verkhov Formation. Tretyachenko noted a distinct rhythmic structure of rocks and identified three transgressive cyclites at 456–406 m. Such structure is typical of basal rocks of the Erga Formation. Therefore, we draw the base of this formation in Borehole 770 at a depth of 456 m.

In a similar manner, we conducted the subdivision and correlation of Borehole 772 section (Fig. 2). The Upper Vendian rocks occupy here interval 993–19 m.

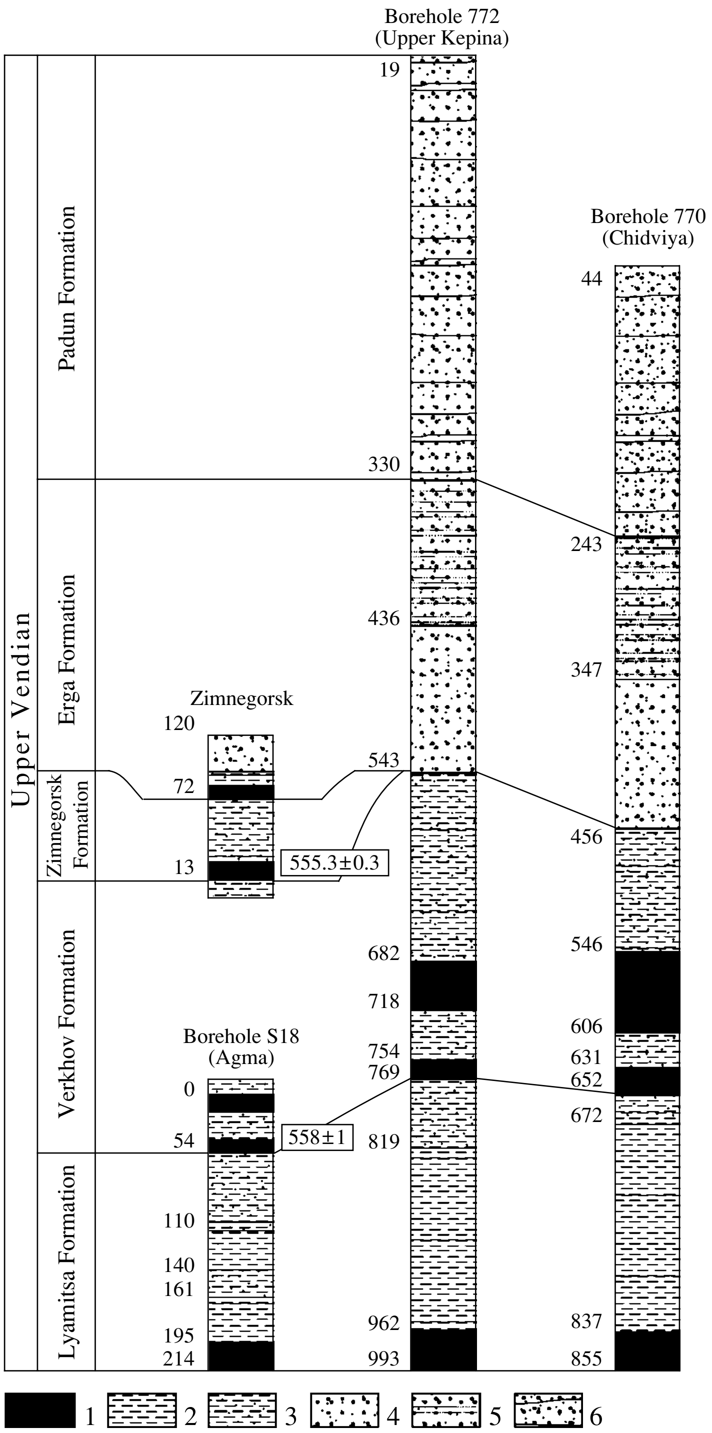

Fig. 2. Subdivision and correlation of borehole sections and summary section of the Zimnegorsk area with the U–Pb zircon age (Ma) of volcanic ash interlayers (numerals in boxes). (1) Thin-bedded clays; (2) fine uniform intercalation of siltstones and clays; (3) intercalation of wavy-bedded sandstones, siltstones, and clays; (4) intercalation of cross- and wavy-bedded sandstones and siltstones with subordinate clay interlayers; (5) mainly thin-bedded and horizontal-bedded sandstones; (6) mainly coarse-platy sandstones.

The underlying rocks were penetrated down to a depth of 1064 m as a unit of intercalating variegated sandstones, brown siltstones, brown, grayish green, or black mudstones, and silty marlstones of the Tuchkino Formation (Yakobson *et al.*, 1991). Microfossils of the Late Riphean appearance were found in mudstones of the Tuchkino Formation (Sivertseva, 1993). The Upper Vendian rocks are overlain by Carboniferous limestone.

Boreholes 770 and 772 unequivocally correlate with each other. They are characterized by thinning of sandy rocks and thickening of clay units in the southward direction.

CHARACTER OF WEATHERING IN PALEODRAINAGE SYSTEMS AND PALEOCLIMATIC CONDITIONS IN THE LATE VENDIAN

Geochemical Indicators

The maturity degree of pelitic and psammitic materials was determined from lithochemical data based on 200 complete major element analyses of clay and sandstone samples taken from boreholes 770 and 772. The analyses were carried out with the XRF method at the Central Laboratory of Sevzapgeologiya Industrial Geological Association. Alkali metals were determined by flame photometry. The classification diagrams were constructed from chemical analyses of clays and sandstones. Then we calculated the hydrolyzate module HM = $(Al_2O_3 + TiO_2 + Fe_2O_3 + FeO)/SiO_2$, Al–Si module AM = Al_2O_3/SiO_2, and the following indices of chemical composition alteration: CIA = $100 \times Al_2O_3/(Al_2O_3 + CaO^* + K_2O + Na_2O)$, CIW = $100 \times Al_2O_3/(Al_2O_3 + CaO + Na_2O)$, and IVC = $(Fe_2O_3 + K_2O + Na_2O + CaO + MgO + TiO_2)/Al_2O_3$. Changes of these parameters were traced throughout the section. The chemical composition and geochemical parameters (CIA, CIW, and IVC values) of the representative clay samples are presented in Table 1.

In terms of lithochemistry, the results obtained show that the Upper Vendian sandstones are commonly immature or moderately mature rocks that can be identified as lithic arenites, sublitharenites, arkoses, subarkoses, and quartz arenites (Fig. 3a). Each formation is characterized by a relatively steady psammitic composition. The compositional variation of sandstones upward the section indicates that the Verkhov sandstones correspond to lithites and arkoses, whereas the Erga Formation combines a wider range of varieties (lithites, arkoses, sublitharenites, and extremely rare quartz arenites). Sandstones of the Padun Formation are generally classified as arkoses, subarkoses, sublitharenites, and subordinate quartz arenites. Thus, the compositional range of sandstones gradually widens upward the section and becomes more mature.

The relatively low lithochemical maturity of sandstones from the Lyamitsa and Verkhov formations of the Belomorian–Kuloi Plateau suggests that the clastic material was derived from cold arid climatic zones that are favorable for feldspar retention. A principally new variety of psammites (quartz sandstones) first appears in sections of the Erga Formation. In the overlying Padun Formation, the quartz sandstones also occur as a subordinate component, but they are more widespread than at the underlying levels. Thus, the gradual upsection decrease in the relative amount of immature psammites may indicate intensification of chemical weathering that affected drainage systems in the Erga and Padun times and, thus, the prevalence of humid environment at the late sedimentation stages. Sochava *et al.* (1992) also noticed that mature terrigenous associations (oligomictic sandstones and hydromica clays) are predominant in the Erga and Padun formations, testifying to sedimentation under conditions of humid climate. Data points of the Upper Vendian clayey rocks plotted on the $\log(SiO_2/Al_2O_3)$–$\log(Fe_2O_3/K_2O)$ diagram (Herron, 1988) concentrate in the fields of clays (the majority of data points) and wackes (Fig. 3b). The latter fields also characterize some intervals in the sections of the Lyamnitsa, Verkhov, and Erga formations. Data points of the Upper Vendian clays from the Belomorian–Kuloi Plateau are localized in the overlap field of hydromica and montmorillonite clays in the TiO_2–TM diagram (Yudovich, 1981). In the FM–SPM diagram (Yudovich and Ketris, 2000), most of the clay data points fall in the field corresponding to the standard three-component chlorite–montmorillonite–hydromica mixture that bears no definite information on paleoclimatic environments. However, some clay samples from the upper part of the Verkhov Formation lie in the field of hydromica clays with a significant admixture of feldspathic particles that characterize products of Precambrian weathering under arid conditions (Yudovich *et al.*, 1991; Yudovich and Ketris, 2000).

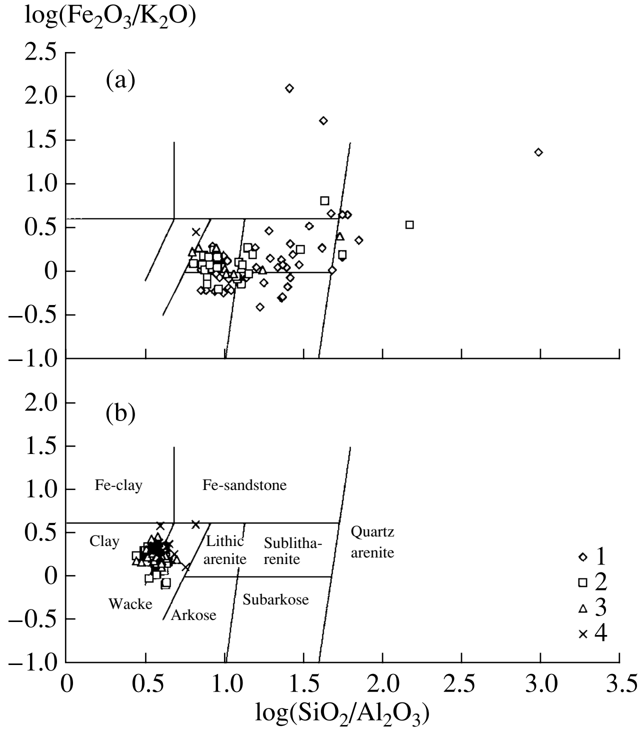

Fig. 3. Data points of Upper Vendian (a) sandstones and (b) clays in the Belomorian–Kuloi Plateau plotted on the $\log(SiO_2/Al_2O_3)$–$\log(Fe_2O_3/K_2O)$ diagram. Formations: (1) Padun, (2) Erga, (3) Verkhov, (4) Lyamitsa.

Let us examine the variation in maturation degree of sandstones and clays in the Upper Vendian succession (from bottom to top).

No certain trend in HM and AM variation was revealed for sandstones in cores from Borehole 770. In sandstones from Borehole 772, such a trend is noted in the upper part of the section. Table 2 shows that both modules gradually diminish upsection and retain approxi-

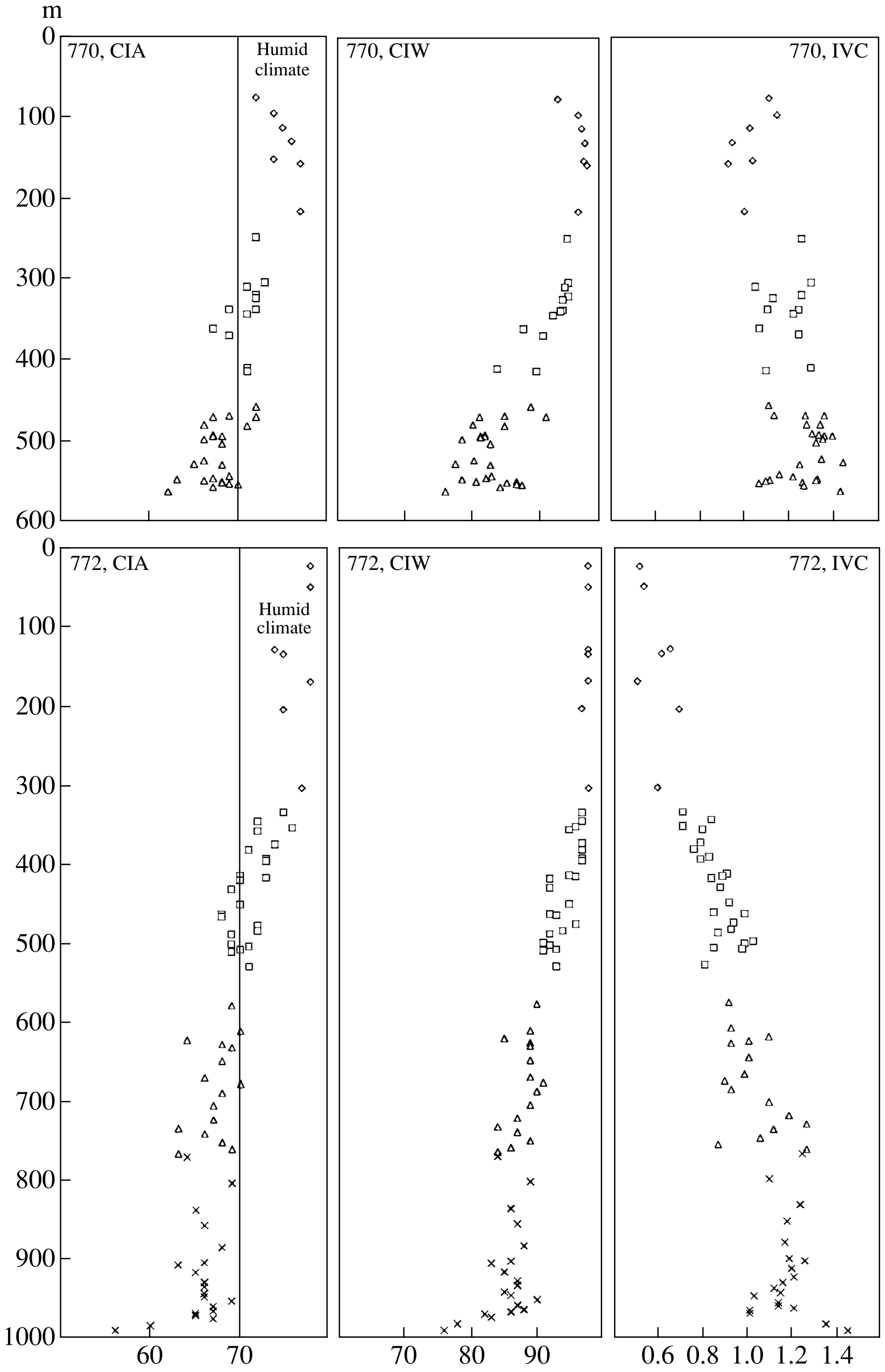

Fig. 4. Variations of CIA, CIW, and IVC indices in clays from boreholes 770 and 772. See Fig. 3 for legend.

mately the same standard deviation (0.21 and 0.14 in the Verkhov Formation; 0.16 ± 0.06 and 0.11 ± 0.04 in the Erga Formation; and 0.07 ± 0.05 and 0.04 ± 0.04 in the Padun Formation). As is known, values of these modules directly correlate with the intensity of provenance weathering and the maturity of sedimentary rocks (Migdisov, 1960; Yudovich, 1981; *Interpretatsiya* ..., 2001). The higher scattering of HM and AM data points and the widening of compositional range of sandstones upward the section, probably, indicate that the drainage area gradually expanded and rocks weathered to different extents were involved in erosion. Thus, lithochemical parameters of sandstones testify to intensification of recycling during the Erga and Padun times.

Analysis of the degree of clay maturity based on the CIA, CIW, and IVC values revealed the following trend. In boreholes 770 and 772, the CIA value of clays

Table 1. Chemical composition of the representative Upper Vendian mudstone samples from the Belomorian–Kuloi Plateau

Component, index	Padun Formation					Erga Formation						Verkhov Formation					Lyamitsa Formation					
SiO_2	60.69	66.56	60.94	61.29	57.68	61.34	60.62	61.88	59.81	59.16	60.69	63.5	58.7	58.28	57.08	57.76	60.61	59.78	58.94	59.9	61.63	68.47
TiO_2	0.88	0.81	0.92	0.87	0.95	0.93	0.85	0.73	0.81	0.8	0.81	0.79	0.84	0.85	0.88	0.84	0.79	0.74	0.98	0.84	0.92	0.61
Al_2O_3	18.75	16.01	18.07	17.53	18.18	16.51	16.45	17.16	16.18	17.38	16.76	16.05	18.53	17.13	17	15.64	15.79	13.63	16.35	16.33	14.6	14.5
$Fe_2O_{3\,tot}$	8.48	6.89	7.55	8.31	10.13	8.6	7.85	5.61	9.4	8.2	7.19	6	7.1	7.82	9	10.31	6.32	6.1	7.9	7.2	7.96	3.91
MnO	0.06	0.03	0.07	0.12	0.08	0.06	0.07	0.05	0.06	0.05	0.05	0.06	0.13	0.09	0.1	0.04	0.09	0.3	0.05	0.1	0.03	0.07
MgO	1.31	1.21	1.71	1.54	2.09	2.25	2.75	3.06	2.67	3.24	2.25	2.57	3.13	3.15	3.67	3.83	3.79	2.94	3.62	3.32	3.44	2.31
CaO	0.22	0.25	0.27	0.28	0.38	0.59	0.58	0.39	0.33	0.36	0.21	0.26	0.93	0.65	0.62	0.86	1.35	4.33	0.74	0.34	0.65	1.31
Na_2O	0.08	0.08	0.09	0.08	0.09	0.23	0.24	0.29	0.61	0.67	0.99	1.5	1.43	1.55	1.53	1.42	1.56	2.2	1.9	1.43	1.63	1.96
K_2O	4.39	3.62	5.21	4.71	4.82	4.46	5.01	4.88	4.93	4.7	4.45	3.91	3.66	4.02	4.21	3.56	3.67	2.53	3.58	3.91	3.59	2.14
P_2O_5	0.05	0.06	0.06	0.09	0.05	0.18	0.24	0.14	0.07	0.13	0.06	0.07	0.16	0.17	0.14	0.16	0.56	0.17	0.19	0.1	0.15	0.08
L.O.I.	4.59	3.97	4.61	4.67	5.05	4.36	4.84	5.21	4.63	4.81	6.01	4.71	4.9	5.78	5.27	5.09	4.96	6.78	5.25	7.03	4.91	4.14
Total	99.5	99.49	99.50	99.49	99.50	99.51	99.50	99.40	99.50	99.5	99.47	99.42	99.51	99.49	99.5	99.51	99.49	99.5	99.5	100.5	99.51	99.5
CIA	78	78	74	75	75	72	70	73	70	72	71	69	70	68	67	67	64	49	66	69	65	65
CIW	84	83	80	81	77	73	69	67	67	65	69	64	64	62	59	56	56	55	57	60	56	61
IVC	0.81	0.81	0.92	0.92	1.05	1.13	1.22	1.10	1.28	1.23	1.09	1.16	1.17	1.30	1.44	1.61	1.50	1.95	1.46	1.31	1.56	1.18

Table 2. Median values of CIA, CIW, and IVC indices and their standard deviations in the Upper Vendian mudstones from boreholes 770 and 772 on the Belomorian–Kuloi Plateau

Index	Borehole 772			
	Lyamitsa Formation	Verkhov Formation	Erga Formation	Padun Formation
CIA	66 ± 4.6	68 ± 2.3	71 ± 2.0	77 ± 1.7
CIW	56 ± 1.7	62 ± 3.6	69 ± 4.0	81 ± 2.8
IVC	1.5 ± 0.2	1.3 ± 0.2	1.1 ± 0.1	0.86 ± 0.1
Index	Borehole 770			
		Verkhov Formation	Erga Formation	Padun Formation
CIA		67 ± 2.4	71 ± 1.6	75 ± 2.0
CIW		82 ± 3.6	93 ± 3.3	96 ± 1.0
IVC		1.3 ± 0.1	1.2 ± 0.1	1.0 ± 0.1

distinctly increases upsection (Fig. 4). Most of the Lyamitsa and Verkhov clays have CIA values less than 70. Clays from the lower part of the Erga Formation is characterized by lower or higher CIA values relative to the above threshold, whereas clays in the upper part of this formation and the Padun Formation yield CIA values higher than 70. Since the CIA value is less than 70 for sediments formed under cold climate (Visser and Young, 1990), the results obtained imply that the relatively immature fine aluminosilicate clastics of the Lyamitsa–Verkhov interval are replaced at the Erga–Padun level by more mature fine-grained terrigenous materials, suggesting that the relatively severe (cold?) arid climate gave way to the mild humid climate in ancient drainage basins.

The CIW variation in clays from boreholes 770 and 772 shows a near direct correlation with the CIA variation. CIW values in clays from the Lyamitsa Formation and the lower part of the Verkhov Formation in Borehole 772 range from 55 to 65. Most clay samples from the upper part of the Verkhov Formation have a CIW value of 64–66. In Erga clays, the median CIW value is equal to 67 in the lower section of the formation and slightly higher (72) in the upper section. This parameter is maximal (81) in clays of the Padun Formation (Table 2). The CIW value commonly correlates with the degree of source rock decomposition, i.e., the degree of weathering of aluminosilicate clastics in drainage systems (Harnois, 1988). The CIW value varies from 59 to 76 in the slightly weathered Precambrian basalts and granites, while this parameter is as high as 94–98 in the more weathered rocks. Thus, increase in the CIW value in borehole sections indicates that progressively more mature material was delivered to the sedimentary basin during the Late Vendian.

Variations in the IVC value in clays from boreholes 770 and 772 reveal an opposite trend. The highest median values of this index (1.5 ± 0.2) are typical of the Lyamnitsa clay. Upsection, they gradually decrease to 1.3 ± 0.2 in the Verkhov Formation, 1.1 ± 0.1 in the Erga Formation, and 0.86 ± 0.1 in the Padun Formation. The ICV variation generally reflects the degree of maturity of fine aluminosilicate clastics delivered to the sedimentary basin. The IVC value is more than 1 in immature shales with a high content of nonclayey silicate minerals, whereas the more mature clayey rocks enriched in clay minerals are characterized by lower IVC values (Cox *et al.*, 1995). Hence, the trend mentioned above demonstrates a gradual replacement of immature fine-grained terrigenous rocks by a more mature material. In terms of paleoclimatology, this may imply the change of relatively severe arid conditions by a mild humid climate.

Thus, judging from the mineral and chemical compositions of sedimentary rocks, at least two sedimentation stages may be recognized in the Late Vendian of the Belomorian–Kuloi Plateau region. At the first (Lyamitsa–Verkhov) stage, the immature clastic material was delivered to the basin from a cold and arid provenance. The second (Erga–Padun) stage was marked by the supply of relatively mature aluminosilicate clastics from areas with mild humid climate.

Malov (2002, 2003, 2004) and other researchers have suggested that the initial composition of Vendian rocks in the Mezen Syneclise underwent substantial alterations. In terms of the degree of epigenetic alteration, Upper Vendian rocks can be divided into three zones (from northwest to southeast): (1) maximal alteration zone (the Belomorian–Kuloi Plateau), (2) moderate alteration zone (the western Mezen Syneclise), and (3) minimal alteration zone (the eastern Mezen Syneclise) (Malov, 2003; Fig. 1). Sandstones of the Padun Formation in zone 1 are considered the most altered ones. In this case, the trends mentioned above in the distribution of lithochemical characteristics of the Upper Vendian mudstones and sandstones may be caused by their epigenetic transformation rather than by climate change in provenances.

In order to prove or refute this suggestion, we calculated CIA and CIW indices for the average chemical composition of mudstones based on data in (Malov, 2003; Table 1). The results showed that the CIA and CIW values in the Upper Vendian mudstones from the southeastern Mezen Syneclise (Kotlas area) tend to increase from the Lyamitsa Formation (62–68) to the Padun Formation (73–82). The above parameters similarly vary in Upper Vendian rocks in the Belomorian–Kuloi Plateau. In mudstones of the Ust'-Pinega and Padun formations, the CIA value is 65 and 75, respectively; the CIW value is 77 and 97, respectively. In sections of the Onega Peninsula, this trend is not so evident; however, the uppermost levels of the section are also characterized by more mature rocks. It is worth mentioning that CIA and CIW indices in mudstones of the Belomorian–Kuloi Plateau do not correlate with alteration zones outlined by Malov (2003). Hence, the trends discussed above reflect the real maturing of Upper Vendian rocks under the influence of climatic environments in drainage systems.

Let us analyze the lithological–sedimentological indicators to understand the character of clastic material transport.

LITHOLOGICAL–SEDIMENTOLOGICAL INDICATORS

The Late Vendian sedimentary succession of the southeastern White Sea region is marked by an abrupt facies change at the boundary between the Verkhov and Erga formations expressed in erosion and development of incised valleys filled with clastics of the Zimnegorsk Formation (Fig. 2). This boundary divides the Lyamnitsa–Verkhov Subcomplex largely consisting of shallow-water marine sediments and the Erga–Padun Subcomplex dominated by fluviomarine and alluvial sediments (Grazhdankin, 2003).

The study of compositional and structural features indicate that Upper Vendian rocks of the southeastern White Sea region were generally deposited at the submarine extension of deltas, whereas their subaerial sectors were localized northeast from the study territory (Grazhdankin, 2003). In particular, this follows from the unimodal distribution of paleocurrents deduced from dips of cross-laminas, strikes of scour and channel casts, and traces of sediment erosion by currents. The cross-bedding (230° SW; number of measurements *n* = 10) and strike of scour signs (245° SW, *n* = 12) in fluviomarine sandstones of the upper Verkhov Formation mark onset of the southwestern progradation of the deltaic fan. Measurements of cross-bedding attitude in the Zimnegorsk sandstones indicate that the paleocurrents also flowed from the northeast (210°, *n* = 9). Numerous scour casts are observed along this direction (240°–60°, *n* = 21). Cross-bedding in the channel casts at the base of the Erga Formation also demonstrates runoff from the northeast (230°, *n* = 15) that fits the channel strike (250°–70°, *n* = 22). The dip of cross-bedding in the channel casts upward the section testifies to the steady character of paleocurrents from the northeast (240° NE, *n* = 5) fitting the flow lineation (215°–35°, *n* = 8). In the studied interval of the Padun Formation, the dip of cross-beds in the synclinal cross-bed series (215° SW, *n* = 10) coincides with the orientation of paleocurrent indicators in the underlying rocks. Genetic features of lithotypes in the southeastern White Sea region suggest that the clastic material was transported to the basin by relatively long-lived unidirectional paleocurrents during floods (Grazhdankin, 2003). Together with the distinctly unidirectional character of paleocurrents, persistence in lateral and vertical directions is also typical of the Upper Vendian facies, indicating a rather large dimension of the deltaic distribution system that made up a fan with the southwestern flow from the Kanin–Timan fold–thrust belt. Owing to the dense network of boreholes, the identified facies can be traced in the northeast direction from one section to another for 100 km, at least, to Borehole 202 (Vaizitsa) (Stankovskii *et al.*, 1985). Despite a relatively great thickness of channel sediments on the deltaic plain, these facies have a simple structure. Signs of drying and eolian sediments have not been established in the sections. Hence, the sediments were deposited in the environment of steady and intense year-round drainage under conditions of humid climate (McCormick and Grotzinger, 1993). If the Erga–Padun sediments had been deposited by ephemeral currents in arid climate, the low groundwater level would have hindered the abundance of sandy channel facies.

Indications of long-term river drainage suggest the existence of a vast land massif at that time in the northeast that served as the provenance of clastic material in the northern Mezen Syneclise. A compressive setting was established in the late Neoproterozoic to the northeast of the East European Craton (the Pechora Zone), where the Varanger–Kanin–Timan fold-thrust belt was formed as a result of collisional deformations (Olovyanishnikov, 1998; Puchkov, 1997; Olovyanishnikov *et al.*, 2000; Gorokhov *et al.,* 2001; Roberts and Siedlicka, 2002). The zircon age of postcollisional granites in the Pechora Plate is 550–560 Ma (Gee *et al.*, 2000). This is consistent with the zircon age of 558 ± 1 and 555.3 ± 0.3 Ma obtained for the Upper Vendian volcanic ash from the southeastern White Sea region (Martin *et al.*, 2000; Grazhdankin, 2003). Therefore, one can assume that weakly metamorphosed sedimentary rocks prevailed in the Late Vendian provenance.

The composition of provenance for Upper Vendian rocks of the Mezen Syneclise has not been studied yet. According to our data, arkoses and subarkoses are rather abundant among sandstones of the Erga and Padun formations. At first glance, the above statement comes into conflict with the suggestion that the foldbelt rocks served as a source of the clastic material. However, Petrovskaya *et al.* (1972) deemed that the Moscow Syneclise was fed with basic igneous rocks throughout the Late Vendian. Pirrus (1980) pointed out that the chlorite-bearing schists played a significant role in the northern provenance. These contradictions can be solved with the help of geochemical and other modern methods.

Thus, we suggest that the Late Vendian provenance was situated in a mountainous region under conditions of humid climate and the northeastern East European Craton occupied a low-latitudinal position at that time. This model is consistent with the available paleomagnetic data on the Zimnegorsk section (Popov *et al.*, 2002) and on the dike complex in northern Sweden (Eneroth and Svenningsen, 2004). General geological models proposed in (Hartz and Torsvik, 2002) indicate that the northern East European Craton was also located at relatively low latitudes. Under conditions of distinct climatic zoning, the mountainous provenance at high latitudes should be affected by sharply arid climate, and the result must be imprinted on geochemical indicators. However, our data do not support this inference.

CONCLUSIONS

Upper Vendian successions of the Belomorian–Kuloi Plateau display a prominent trend in variation of the chemical composition of mudstones and sandstones in accordance with sedimentation stages.

Upward the section, the sandstones are characterized by a wider compositional range and higher maturity in terms of lithochemistry and petrography. Sandstones from the Verkhov Formation are composed of lithites and arkoses. Sublitharenites and less abundant quartz arenites appear in the Erga Formation. The Padun sandstones comprise arkoses, subarkoses, and sublitharenites. The contribution of quartz arenites in this formation is higher than in the underlying rocks. The appearance of mature sediments in the Upper Vendian successions coincides with the replacement of shallow-marine facies by fluvioalluvial sediments and the onset of the prominent southwestward transport of clastic material. This may be interpreted as a change of paleoclimatic conditions in the drainage system if the provenances did not change during the entire Upper Vendian. Alternatively, this might be related to the change of provenances. In any case, the data presented above indicate that sandstones in the lower part of the section formed under severe conditions of cold and dry climate. In contrast, clastic material of the Erga–Padun time was delivered from regions markedly affected by the chemical weathering. It is worth mentioning that recycling of psammites intensified in the second half of the Late Vendian. This is in good agreement with indications of numerous scours and formation of a system of deeply incised valleys.

The CIA and CIW values in the Upper Vendian clays increase upward the section, while the IVC value decreases in the same direction as a response to replacement of the relatively immature fine-grained aluminosilicate clastics formed in arid, semiarid, or nival climate by the more mature material derived from regions of humid climate. This change approximately coincides with the boundary between shallow-marine and fluvioalluvial sediments.

Thus, in the Late Vendian, i.e., 555 Ma ago, the northeastern East European Craton was located at relatively low latitudes under conditions of humid climate that was favorable for the wide development of prodeltaic and fluviomarine environments. This conclusion has a fundamental significance for studying the diversity of Ediacarian biota in the East European Craton. All of the known Ediacarian fossil assemblages in Australia and Namibia are related precisely to similar prodeltaic and fluviomarine facies (Grazhdankin, 2004).

Based on results of the paleoecological investigation, Fedonkin (1996, 2003) has proposed an original hypothesis of the origin of the metazoan biota under cold-water conditions. Our results show that the diversity of the Ediacarian-type biota in the southeastern White Sea region reflects conditions of mild humid climate. Therefore, the similarity of paleoecological indications of the Ediacarian organisms with the faunal ecology of the present-day cold-water basins is most likely caused by a combination of other factors unrelated to the paleoclimatic conditions.

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