УДК 552.513.1:551.732(470.23) Вестник СПбГУ. Сер. 7. 2015. Вып. 4

P. V. Fedorov, A. I. Palkina

SURFACE TEXTURES OF SAND GRAINS FROM QUARTZ ARENITE STRATOTYPE SECTIONS OF SABLINKA FORMATION (CAMBRIAN, SERIES 3; SAINT PETERSBURG VICINITY, NORTHWEST RUSSIA): THE KEY TO UNDERSTANDING OF CONTINENTAL PROCESSES AT THE GUZHANGIAN—FURONGIAN BOUNDARY

St. Petersburg State University, 7/9, Universitetskaya nab., St. Petersburg, 199034, Russian Federation

Poorly cemented quartz arenites of Sablinka Formation form a thin sand cover which was formed during the Cambrian time at the shallow fringe of epicontinental Moscow Paleobasin. Surface textures of sand and silt grains from stratotype sections of Sablinka Formation were studied using scanning electronic microscope. Etching and crystalline overgrowth textures were found as predominant on the surface of quartz grains. Since these textures may only form in continental environment, modern continental environments with chemical processes of silica dissolution and deposition were considered. The search for analogs was based on the presence of a system of polygonal subvertical fractures in the top of Sablinka Formation, traditionally considered "desiccation cracks", and the pebbles of densely cemented sedimentary quartzite in the basal layers of the sandstones, overlaying Sablinka Formation. The recent analogs were found in South Australia and west New South Wales: the mature pedogenic silcretes, where the zone of silica concretions (pseudo-breccia and pseudo-conglomerates) is located over the zone with polygonal prismatic blocks. It was concluded that during the continental hiatus similar profile began to form at the top of Sablinka Formation, but maturing of pedogenic silcretes was interrupted by Furongian transgression. The pseudo-breccia and pseudo-conglomerate zone, and the upper portion of the prismatic zone were eroded by the transgressing sea. The time interval of silcrete formation was correlated with the interval of deposition and leaching of Kakeled Limestone Bed within the Alum Shale of the Baltic Paleobasin. Refs. 20. Figs. 10.

Keywords: Cambrian Stage 3, Sablinka Formation, quartz arenites, sand grain surface textures, continental hiatus, silcrete, Baltic-Ladoga Klint.

П. В. Федоров, А. И. Палкина

СТРУКТУРЫ ПОВЕРХНОСТИ ПЕСЧАНЫХ ЗЕРЕН ИЗ СТРАТОТИПИЧЕСКИХ РАЗРЕЗОВ КВАРЦЕВЫХ АРЕНИТОВ САБЛИНСКОЙ СВИТЫ (КЕМБРИЙ, СЕРИЯ 3; ОКРЕСТНОСТИ САНКТ-ПЕТЕРБУРГА, СЗ РОССИИ): КЛЮЧ К ПОНИМАНИЮ КОНТИНЕНТАЛЬНЫХ ПРОЦЕССОВ РУБЕЖА ГУЖАНГ—ФУРОНГИЙ

Санкт-Петербургский государственный университет, Российская Федерация, 199034, Санкт-Петербург, Университетская наб., 7/9

Слабо сцементированные кварцевые арениты саблинской свиты слагают маломощный песчаный покров, который был образован в кембрии на мелководном северном обрамлении эпиконтинентального Московского палеобассейна. С помощью сканирующего электронного микроскопа исследованы поверхностные структуры песчаных и алевритовых зерен из стратотипических разрезов саблинской свиты. Установлено, что доминирующими структурами поверхности зерен являются структуры растворения и кристаллического обрастания. Поскольку такие структуры образуются только в континентальных условиях, были рассмотрены современные континентальные обстановки, в которых действуют химические процессы растворения и отложения кремнезема. При поисках аналогов принималось во внимание наличие полигональной системы субвертикальных трещин в кровле саблинской свиты, традиционно считающихся «трещинами усыхания», а также гальки плотно сцементированных осадочных кварцитов, в базальных слоях перекрывающих саблинскую свиту песчаников. Современные аналоги были обнаружены на севере Южной Австралии и на западе штата Новый Южный Уэльс: это зрелые педогенные силкреты, в вертикальном профиле которых зона кремнистых стяжений (псевдобрекчий и псевдоконгломератов) располагается над зоной с полигональной призматической отдельностью. Сделан вывод, что во время континентального перерыва в кровле саблинской свиты начал формироваться аналогичный профиль, однако вызревание педогенных силкретов было прервано фуронгской трансгрессией. Зона псевдобрекчий и псевдоконгломератов, а также верхняя часть призматической зоны были переработаны наступающим морем. Временной интервал образования силкретов сопоставлен с интервалом накопления и выщелачивания известняков Какелед, принадлежащих формации квасцовых сланцев Балтийского палеобассейна. Библиогр. 20 назв. Ил. 10.

Ключевые слова: кембрий, отдел 3, саблинская свита, кварцевые арениты, структура поверхности песчаных зерен, континентальный перерыв, силкреты, Балтийско-Ладожский глинт.

Introduction

Poorly consolidated quartz arenites of Sablinka Formation form a thin (1–16 meters) laterally extended unit in the northwestern portion of the sedimentary cover of the East European Platform. They are found in outcrops along the Baltic Klint to the south and to the east of Saint Petersburg.

The results of the first very thorough study of structural and textural features of these sandstones were published by L. B. Rukhin in 1939 [1]. In the section of his article on the morphology of sand grains, Rukhin described two distinct type of grain surface, visible in optical microscope, which he named "fine-pitted" and "polished". According to Rukhin, these two types may be present in individual grains or can coexist in the same grain; in the latter case the shiny "polish" overlays the pre-existing fine-pitted surface. Rukhin explained formation of the fine-pitted type by long wind transport, with multiple collisions of grains in the air. The polishing of the surface, according to Rukhin, took place after aeolian abrasion and evidences more or less long transport of sand grains over the bottom of a shallow basin.

The purpose of our study was to systemize the surface textures of quartz grains from Sablinka Formation stratotype sections using a scanning electron microscope and to interpret the results based on all available geological data.

Geological Overview

The Late Vendian, Cambrian, Ordovician, and Devonian sedimentary rocks, which form the northwestern fringe of the plate cover of the East European Platform, near the boundary with the Fennoscandinavian Shield, are found in numerous small outcrops in the vicinity of St. Petersburg. The Vendian, Cambrian and Early Tremadocian deposits consist of poorly consolidated terrigenous rocks. The overlaying Ordovician strata consist mostly of limestones. The Vendian, Cambrian and Ordovician rocks dip with very low angle (2–3 m/km) to S-SE. The Devonian deposits consist of sand, sandstones and clay with thin interbeds of limestone and marl; they dip to S-SE with even lower angle (1.5–2 m/km), overlaying Ordovician and, in some areas, Cambrian and Vendian rocks with azimuthal unconformity [2].

The Ordovician limestones, being the strongest of the rocks here, form a slightly elevated Ordovician plateau, which is divided into western and eastern segments. To the south and to the east the rocks of the plateau gently plunge under the Devonian deposits, and in the north they are cut by the Cenozoic preglacial denudation cliff, known as "Baltic Klint" [2]. In the vicinity of St. Petersburg area the Klint is largely quite gently sloped with sublatitu-

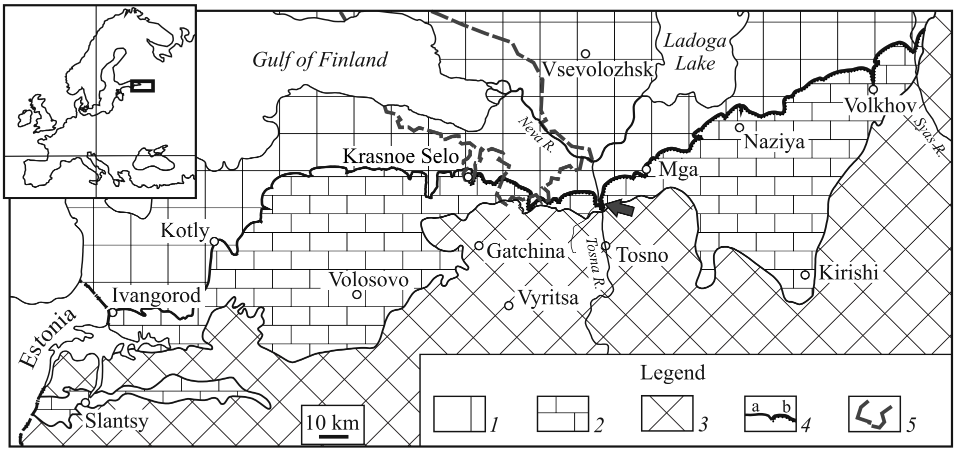

Fig. 1. Schematic geological map of St. Petersburg area:

1 — Vendian and Lower Cambrian; *2* — Ordovician ; *3* — Devonian ; *4* — Baltic Klint line, a — Sablinka Formation absent, b — Sablinka Formation present; *5* — St. Petersburg city limits. The location of studied stratotype sections of Sablinka Formation is marked with the arrow.

dinal trend 3–20 km south of the Gulf of Finland, the Neva River and Lake Ladoga (Fig. 1). The plain north of the Klint is formed by gray clays of Vendian Kotlin Horizon and blue clays of Cambrian Lontova Formation (Terrenuvian, Stage 2). The Klint escarpment is formed by sand strata of Cambrian age up to the bottom of Tremadocian, overlain by bituminous Dictyonema Shales of Low Tremadocian and glauconitic sandstones of Middle Tremadocian — Lower Floian. The crest of Klint is reinforced by limestones of Middle Floian — Darriwilian.

The outcrops of the strata forming the Klint are associated with valleys of numerous rivers and streams, flowing from the Ordovician plateau to the Gulf of Finland, the Neva River and Lake Ladoga.

The cover of quartz arenites of Sablinka Formation can be traced in natural outcrops approximately from Krasnoye Selo meridian (formerly a town, now a suburb of St. Petersburg) in the west, to the Syas River valley in the east (Fig. 1). The arenites are inequigranular, predominately fine, porous. The content of allothigenic heavy minerals, mostly, zircon, rounded tourmaline and ilmenite, is very low. Most of the arenites has no mineral cement, which can be visible under regular optical microscope. The arenites withstand surface erosion well, but may be easily crushed to loose sand by impact. The color of Sablinka arenites is predominantly subdued pink, yellow, or red, with some bleached spots. Colored grains are covered with very thin film of iron hydroxides. The bleached varieties contain over 99% of quartz, and were widely mined in the 19th century for glass production.

Sablinka arenites lay with deep hiatus over smooth surface of the blue clay of Lontova Formation. They are overlain by Obolus quartz sandstones of Ladoga Formation (Furongian), or, in a few places where Ladoga Formation is eroded, by Obolus sandstones of Tosna Formation (terminal Furongian — lower Tremadocian) with evident signs of erosion [3].

All Vendian and Lower Paleozoic formations mentioned above deposited in the epicontinental sea, which covered a substantial part of the Baltic continent. The geologists of the Northwestern Europe traditionally believe that this sea was divided into two interconnected basins: Baltic Basin and Moscow Basin [e.g. 4]. Both paleobasins covered relatively deep depressions with fringing/dividing shallows. The bed of Sablinka arenites was formed at the northwest flank of the Moscow depression [5].

It is not possible to accurately determine the time period of the deposition of Sablinka Formation based on endemic acritarchs and skeletal fossils, i.e. technically it may span any part of the interval between the biostratigraphically dated deposits of Late Terrenuvian and Furongian. However, during Cambrian Epoch 2 the epicontinental sea regressed to the west of the East European Platform, with several rapid and drastic changes of its outlines and depocenters [6]. The long predominantly highstand interval with relative tectonic stabilization of the region, marked by deposition of Alum Shale Formation spans Cambrian Epoch 3, Furongian and Lower Tremadocian. The beginning of this interval confirmed at the bottom of *Ptychagnostus gibbus* Biozone [7]. Beginning of the subsequent post-Terrenuvian sea transgression into the Moscow depression and deposition of Sablinka sandstones at its fringes prior to this boundary is unlikely.

Sablinka Formation in the Stratotype Area

Sablinka Formation was described by Rukhin [1] in sections along Sablinka and Tosna rivers, in the area where the former meets the latter; the formation is named after the Sablinka River.

In the stratotype area the Formation is formed by a sequence of three members (Fig. 2).

Lower Member (up to 3 meters) corresponds to members E and D, without D_1^1 as per Rukhin [1] and lower member of the Lower Sub-formation as per L. E. Popov et al. [3]. The member consists mostly of fine sandstones with interbeds and patches of clayey siltstones. The sandstones of the member are the least well sorted; their beds contain visible amount of silt (5–25%) and coarse sand (0–25%) fractions. Rare well-rounded coarse sand grains and grains of quartz gravel are distributed in the lower half of the member. The following bedding types are typical: horizontal, wave, ripple mark, parallel cross-bedding, flaser and trough. Lenticular bedding occurs in the clayey siltstones. There are rare series of cross-bedding with various orientations, formed by coarse sandstones. The lamination of some beds is disrupted by cryptobioturbation.

Flattened pebbles of blue Lontova clay are often found in the bottom beds. Inclusions of sulphides of iron, zinc, lead, and small vugs filled with clear ankerite are also dispersed within this layer. Ankerite cements the sandstones of the lower member locally. Additionally, small brownish dense rounded concretions of sandstone formed around fine microscopic pyrite particles are scattered throughout the member. Sometimes these concretions are grouped in thin stratiform banded aggregates, with rusty colors on the surface.

Apparently, deposition of the sandstones of the lower member took place on wide and very gently sloped low-energy littoral and upper sublittoral, in the environment of low tide range and weak impact of waves and currents. The absence of fauna suggests that the portion of the basin where the sandstones deposited was highly desalinated.

Local ankerite cementing and inclusions of sulfides are the result of Caledonian or later migration of low-temperature hydrothermal solution above the Lontova aquiclude.

The transition from the lower member to the middle member is gradual, and is marked with intermittent cross-bedding and horizontal beds in the section. We place the boundary between these two members at the top of the uppermost sandstone bed with horizontal bedding.

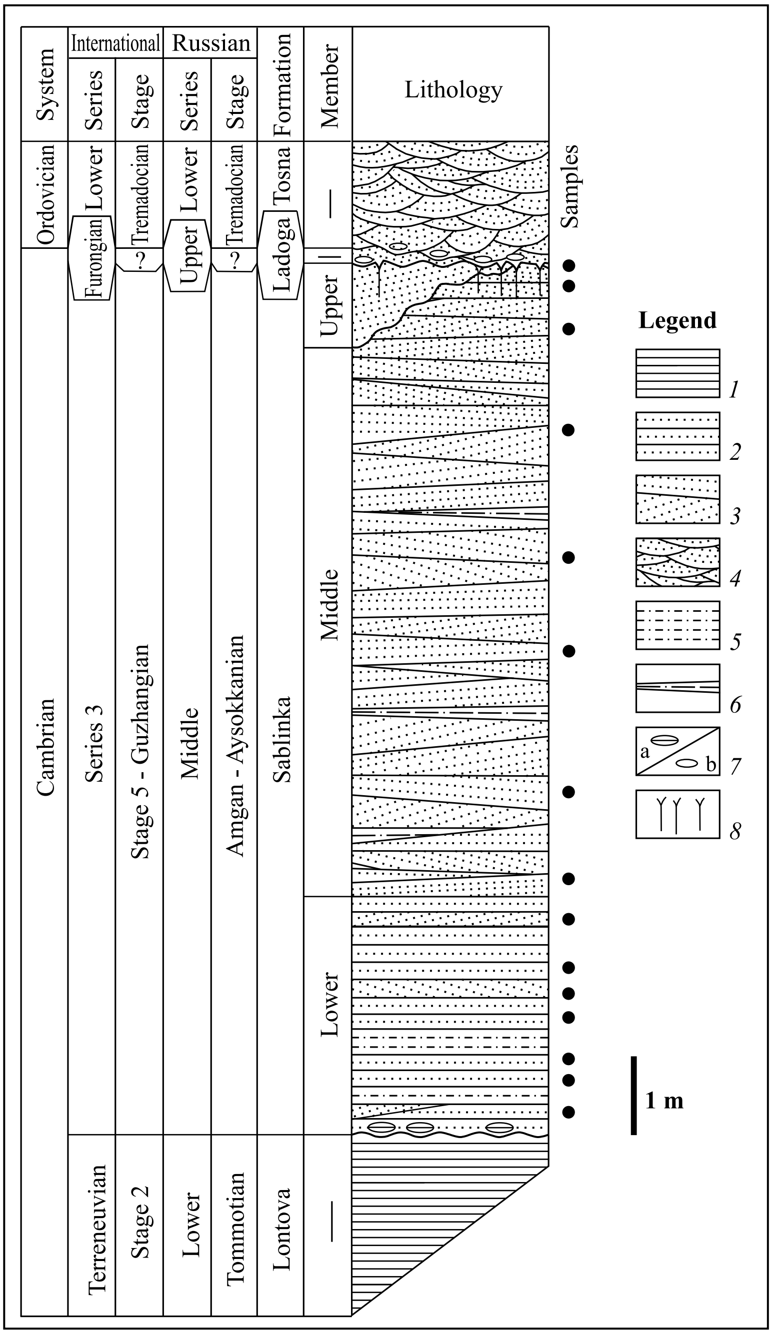

Fig. 2. Summary section of Cambrian—Tremadocian sandstones in the stratotype area of Sablinka Formation:

1 — blue clay of Lontova Formation; *2–4* — sandstones: *2* — parallel cross-bedding; *3* — predominantly horizontal bedding; *4* — trough-bedding; *5* — clayey siltstone; *6* — lenticular clay interbeds; *7* — pebbles: a — Cambrian clay; b — sedimentary quartzite; *8* — fractures at the top of Sablinka Formation.

Middle Member (up to 8.5 meters) corresponds to D_1^1 and member C, excluding beds C_1^{1-3} as per Rukhin [1], or upper member lower sub-formation as per Popov et al. [3]. This member consists predominantly of fine sandstone, with significant share of medium sand fraction and minor content of fine sand. Typical structural pattern is defined by thin (0.05–0.15, rarely up to 0.3 meters) series of parallel cross-bedding. The cross bed dip direction varies significantly, while the angle is not more than 25°, and the cross-bedding series themselves can usually be traced for several meters. There are data indicating overwhelming predominance of two opposite dip directions of cross beds [8], but in our opinion they need to be verified, since such distribution of bed dip directions was denied even by Rukhin [1].

Lenses and patches of dark gray and greenish gray sandy clays up to 3–4 cm thick extending for several meters laterally sometimes occur within the member at the boundaries of cross-bedded series. Their lateral boundaries are always erosional. Endemic acritarchs, not known outside of the Sablinka Formation, were found in these clays [3].

Local stratiform bands with ferrous cementation around small pyrite nodules are present at the bottom of the member, similar to the lower member. Additionally, there are subhorizontally oriented lenticular bands of tough sedimentary quartzite in the upper portion of the member, which in the ourcrops reach 0.5–3 meters in length, and are up to 0.4 meters thick. The bedding within these masses conforms with the bedding of the enclosing poorly consolidated sandstones.

The deposition environment of middle member was, apparently, shallow desalinated sea, where laminar currents moved sand along the bottom, forming low subsea dunes with even crests. The clay was deposited from the suspension during the periods when the currents stopped.

Upper Member (0–2.2 meters) is equivalent to C_1^{1-3} as per Rukhin [1] or Gertovo member of the upper sub-formation as per Popov et al. [3]. The member is distinguished from the previously described by the presence of whole obolid shells, which, however, do not form massive aggregates, as well as by significant thickness fluctuations and local variations of grain size composition. This member is absent in half of the outcrops within the stratotype area. Where the member is thin, it consists mostly of fine sand fraction, predominantly with trough cross-bedding, rarely horizontal bedding. Conversely, where the member is approaching the maximum thickness the size of sand grains visibly increases. Coarse-grained varieties can be seen at the bottom of these sections; however, the medium-grain sandstones predominate, forming series of plane-parallel cross-bedding 0.4–1.1 meters thick. There are interbeds of dark gray clay (1–10 cm) within the cross-bedded series and, sometimes, at the bottom of the member. Flat and rolled-up clay flakes and wrinkled waterflooded sand flowing structures are typically found in these sandstones. Bioturbation is local and poorly developed.

In several outcrops the sandstones of upper member and top of the middle member, together with the overlaying sandstones of Ladoga and Tosna formations, have solid or lumpy iron oxide cementation, resulting in brownish-red coloration of the sandstone. The location of this superimposed cementation, according to our data, coincides with the local fractured karst zones in the overlaying limestones.

Endemic acritarchs were described in the clays at the bottom of the member [3]. The brachiopods are represented by inarticulate endemic species *Obolus ruchini* and *Oepikites macilentus* [3]. Additionally, fragments of phosphate tubes of hyolithelminthes [3, 9] and Cnidaria of *Sphenothallus* genus were found in the upper member. Ichnofossils are represented by two genera [10] with very wide age and facies distribution.

The sandstones of the upper member deposited in the environment that was significantly different from that of the arenites of the lower and middle members. Prior to their deposition the deposition surface landscape was significantly dissected, which is reflected in simultaneous changes of thicknesses and facies of the sandstones in the upper member.

The appearance of marine skeletal fossils indicates increased salinity and better connection with the open sea.

Regressions detected at the boundaries of middle and upper members of Sablinka Formation, as well as Sablinka and Ladoga formations, left their mark in Alum Shale of the adjacent Baltic Paleobasin. The first resulted in formation of Exporrecta Conglomerate Bed, Hyolites and Andrarum Limestone Beds. The second corresponds to the hiatus with deposition of shallow-sea Kakeled Limestone Bed [7].

Obolus sandstones of Ladoga Formation (0–0.4 meters) lay on the surface of middle and upper members of Sablinka Formation with erosional contact. In the areas where the thin cover of Ladoga Formation was eroded, Sablinka Formation is overlain by Obolus sandstones of Tosna Formation, also with signs of erosion. Accumulations of Obolus detritus, numerous pebbles and cobbles of dense sedimentary quartzite and pea nodules of iron hydroxides are associated with the bottom of the overlaying formations. The pebbles and cobbles very rarely have regular spherisity. Sometimes tabular, elongated or conical specimens are found, and some of the latter are shaped as pyramids with rounded angles. However, most often the pebbles have pitted and hummocky surfaces, with all angles significantly rounded. The pebbles are colored brownish red by iron hydroxides.

The inarticulate brachiopod complex of the basal layer often contains redeposited brachiopod shells from Sablinka Formation [3].

In many outcrops the top of Sablinka Formation is dissected by thin ferruginized subvertical fractures, extending up to 2 meters deep. Laterally, the fractures form polygons from 0.3 to 1.5–2 meters. Their mouths have wide wedge-shaped opening, creating erosional pockets filled with basal sandstones from the overlaying strata. Usually they are compared to desiccation cracks [3]. The presence of the fractures indicates that the sandstones of Sablinka Formation were consolidated before the beginning of Ladoga Formation deposition.

Material and Study Methods

We collected 14 spot samples of arenites along Sablinka Formation section near the junction of the Sablinka River and Tosna River, approximately 200 grams each (Fig. 2). The samples were collected after removing loose weathered layer from outcrop surface. The lower member was sampled on the left bank of the Sablinka River, 300 meters above the mouth; the middle member was sampled on the left bank of the Tosna River, 130 meters above the junction with the Sablinka River, upper member on the right bank the Sablinka River in 1400 meters above the mouth. During sampling the sandstones easily fell apart into individual grains and became loose sand, which, as mentioned above, is normal for Sablinka Formation.

The sand was washed in distilled water, dried and separated into standard size fractions (from 3 to 6) using a set of sieves. Each fraction was weighted to determine its content in the sample. 400 grains from each sand fraction were studied under an ordinary optical binocular microscope to assess rounding degree and quartz grain surface characteristics. 1–2 most typical grains were selected from each fraction. Grain aggregates and certain rare atypical irregularly shaped grains were also selected. Total of 90 specimens were selected. Surface microtextures of the selected grains and aggregates were studied using scanning electronic microscope Hitachi TM 3000 without coating. Images were captured at various magnifications. This research was performed at the Center for Microscopy and Microanalysis of Research Park of St. Petersburg State University.

Results and Discussion

Under optical microscope it can be seen that sand particles from Sablinka Formation consist of clear quartz grains; milky grains are found as an exception. Only one rounded corroded orthoclase grain was found among the numerous studied grains of quartz. Most of medium to very coarse grains are rounded and well rounded, with high to medium sphericity. However rounded grains with lower sphericity, elongated or irregular shape, are often present as well. The quartz grain surface, as first described by Rukhin [1], looks shiny or fine-pitted, and grains usually have areas of both types.

The fine and very fine particles are less rounded, many of them appear semi-angular or angular; rounded grains are rare. Fine-pitted grains in these fractions are rare, and most of them have shiny surface.

During the SEM study it was found that surface textures, formed by mechanical interaction during sand transport were preserved only on a few, predominantly medium and coarse particles. Out of many signs of mechanical interaction [11–13] only crescentic gouges (Figs. 3A, C; 5C, D) and straight and curved abrasion scratches (Fig. 5D) were found in some of the grains. Crescentic gouges are a type of Herzian fractures and are considered as evidence of high-energy underwater percussion marks [14]. The abrasion scratches are most often caused by dragging of grains over the sand surface.

It was found that the most predominant features of grain surface in Sablinka Formation are selective etching and syntaxial quartz overgrowth textures of chemical origin.

The selective etching textures are represented by pits, parabolic arches, furrows, and irregular depressions. The conically shaped etch pits 0.5–5 micron in diameter and 0.5–7 micron deep are distributed along grain surface irregularly, always in groups. Their axes are usually parallel, evidently following certain crystallographic directions (Figs. 3–7). Sometimes smaller pits merge into larger pits (Fig. 3D).

The parabolic etch arches are located on surfaces oriented at a small angle relative to the orientation of the closest etch pit axes (Fig. 4C, D; 7C).

The furrows were formed along fractures of various origin (Figs. 3D; 4A, B; 6A—D; 7A, B) and the edges of crystals in polycrystalline grains (Figs. 4 C, D) as a result of their widening by etching.

Irregular depressions (Figs. 4 A, B) are seen rather rarely, possibly inheriting the forms or defects that occurred during crystallization or metamorphism.

All the etching textures mentioned above give the grains of Sablinka sandstones their distinctive appearance, which looks as fine-pitted under optical microscope.

The crystalline overgrowth textures in sand grains are usually seen as differently sized fragments of facets (Figs. 5C, D; 6A—D), creating illusion of polishing by their lustre.

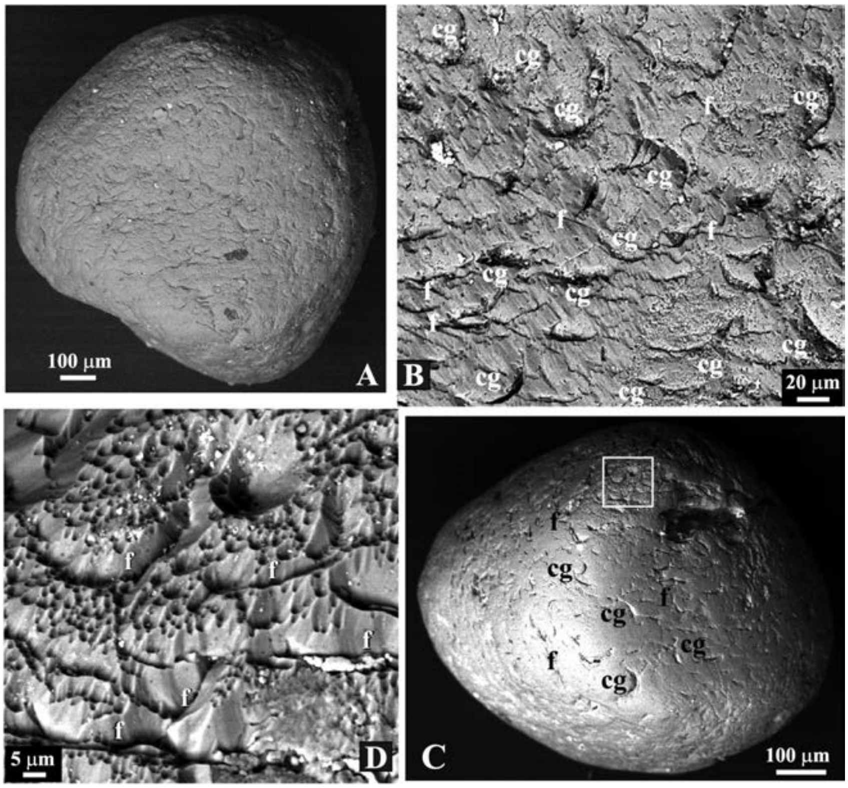

Fig. 3. Micrographs of quartz sand grains from Sablinka Formation. (A) Rounded grain with low relief, crescentic gouges, furrows, and percussion marks. (B) Detail of A with larger magnification: crescentic gouges (cg) and furrows (f) on the surface with barely visible etching pits and parabolic arches. (C) Rounded coarse grain with several crescentic gouges and furrows. The etched area is localized at the top. (D) Part of the etched area of C within the rectangle. Note numerous etch pits and furrows (f)

The thickness of the overgrowth layer varies from 1 to 10 micron. Fully faceted sand fraction grains are very rare (Fig. 8), however, silt grains (when present) are better faceted than grain particles (Figs. 5B; 7C, D).

Signs of abrasion of facet angles were absent in all studied grains. An interesting feature of crystalline overgrowth of the quartz grains from Sablinka Formation is the formation of additional small facets around various mechanical defects: crescentic gouges, abrasion scratches, furrows and etch pits (Figs. 5D; 6B, D; 7B).

Generally, we may say that each quartz grain from our small set was affected by etching and crystalline overgrowth processes to some degree. These chemical processes apparently took place simultaneously (in geological time scale) over various areas of each grain. One of the outcomes was erasing of transport marks on most grains. The other outcome was cementation of the sand strata. Thin layers of crystalline overgrowth of adjacent grains formed microscopic patches of contact cement which creates poor consolidation observed in the most of Sablinka sandstones. The minimum content of the contact cement lead to high residual porosity, which created favorable conditions for local carbonate and ferruginous cementation during later stages.

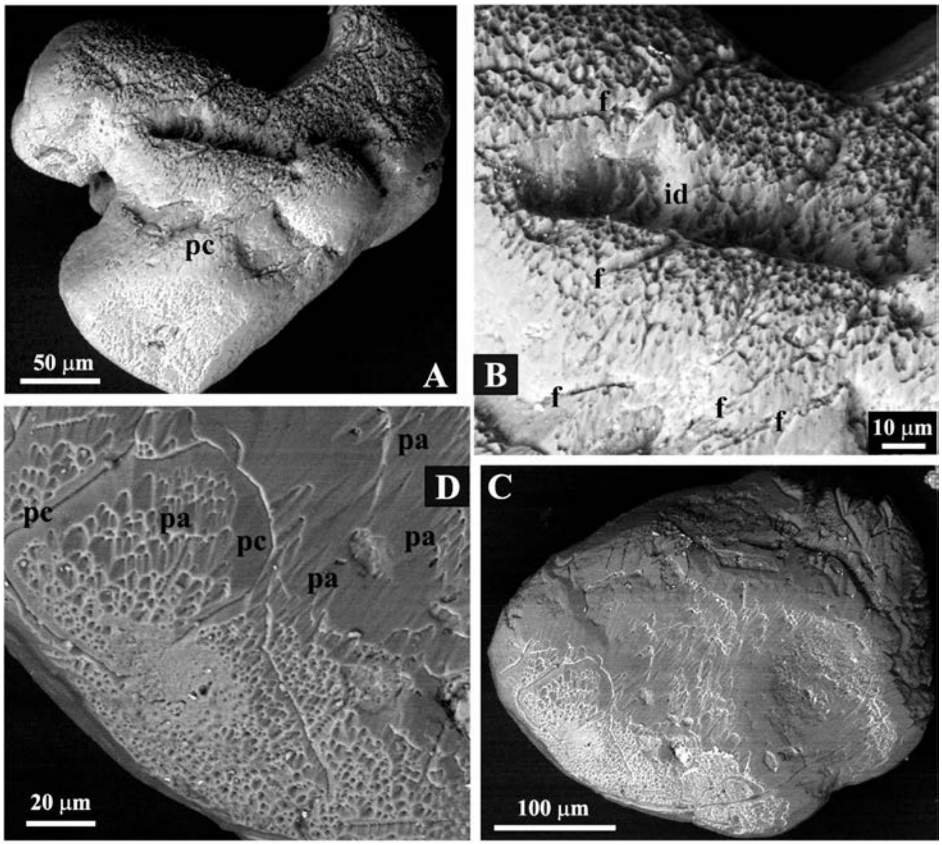

Fig. 4. Two quartz grains from Sablinka Formation. (A) Atypical sub-angular grain, probably polycrystalline Japanese twins with pronounced topographically irregular surface. (B) Part of A under larger magnification. Strong dissolution features are clearly distinguishable: irregular depression (id), furrows over cracks (f) and numerous etch pits. (C) Sub-rounded grain with features of quartz dissolution and deposition on the surface. (D) Part of C. Etching pits, parabolic arches (pa) and furrows (f) are visible. Left of the center, within the polygonal area surrounded by furrows, it is clearly visible that orientation of pits and arches is somewhat different from the other part of the grain. This indicates the presence of polycrystalline contact (pc).

Redistribution of silica along the depth of Sablinka Formation certainly took place in a continental environment, which was predominant during long regression of the sea. Out of two hiatuses: at the boundary between the middle and the upper members of Sablinka Formation and at the boundary between Sablinka and Ladoga Formations, the latter is the most pronounced. This hiatus is characterized by large-scale occurrence of cementation, the development of polygonal system of vertical fractures at the top of Sablinka Formation (Fig. 9), and abundant quartzite pebbles at the bottom of the overlaying sediments. Deep lowering of the sea level during this hiatus is confirmed even in the sections of Alum Shale of the Baltic Basin, where it is marked by wide development of karst in Kakeled Limestone Bed [15].

The sands on the surface of the desert formed in place of the regressed Cambrian sea were not redeposited by aeolian processes. Possible cause is the drastic weakening of atmo-

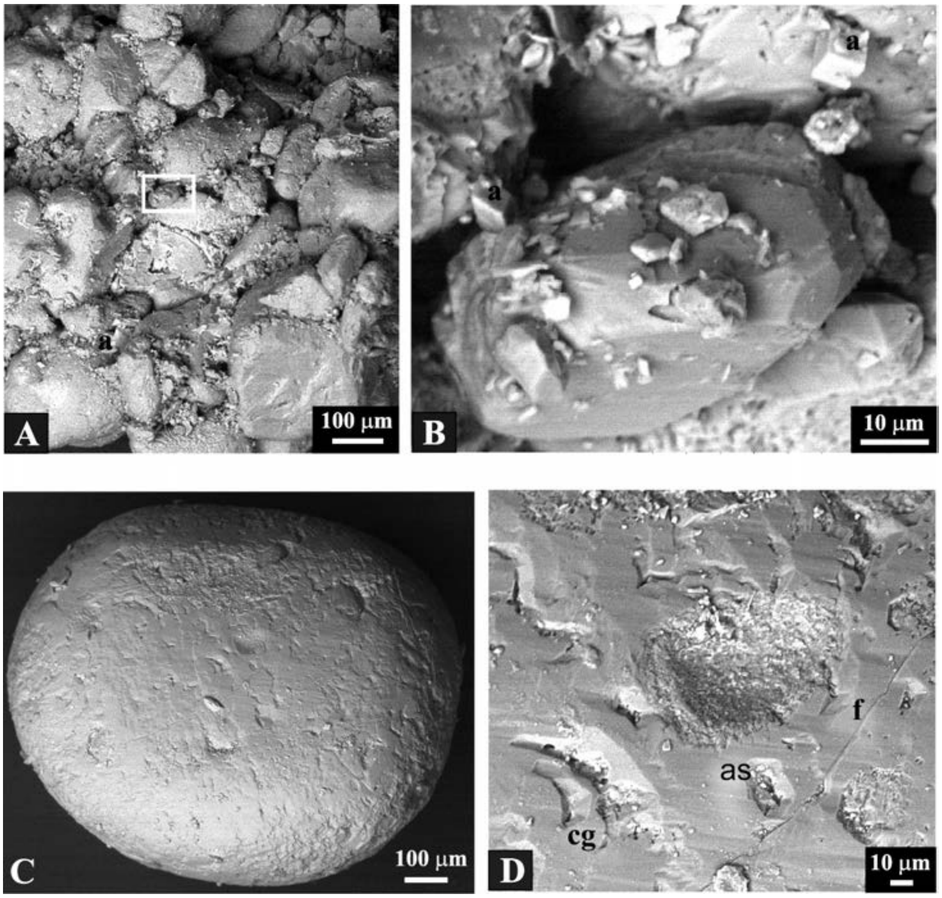

Fig. 5. Quartz grains from Sablinka Formation. (A) Inequigranular sandstone with particles of silt, clay, iron hydroxides and ankerite crystals on the grain surface from the lower member. (B) Enlarged detail, shown as a rectangle in A. The silt particles are almost fully faceted. (C) Very large well rounded grain with smooth "polished" surface. (D) The same surface with larger magnification. Clearly visible is the thin film of crystalline overgrowth, forming facets around the crescentic gouges (cg), abrasion scratches (as), and furrows (f), which existed on the grain surface prior to overgrowth. Even smaller facets are visible around the etch pits. Large shallow depression in the center marks the area of contact with the adjacent grain, and is not affected by the overgrowth

spheric circulation during Late Guzhangian and Furongian, which, in turn, was a result of maximum concentration of carbon dioxide in the air in Phanerozoic history [16].

The cover of immobile sand at the surface of the continent became an arena for chemical processes. It is unlikely that those processes were much different from the processes that take place in desert regions now. If we look for recent analogs, we inevitably choose arid landscapes of South Africa, Central and South Australia, where topsoils and saprolites with silica cement, known as "pedogenic silcretes" are formed [17].

Formation of pedogenic silcretes is a result of numerous repeating cycles of dissolution of silica by rainwater with subsequent transportation and deposition. There are two key

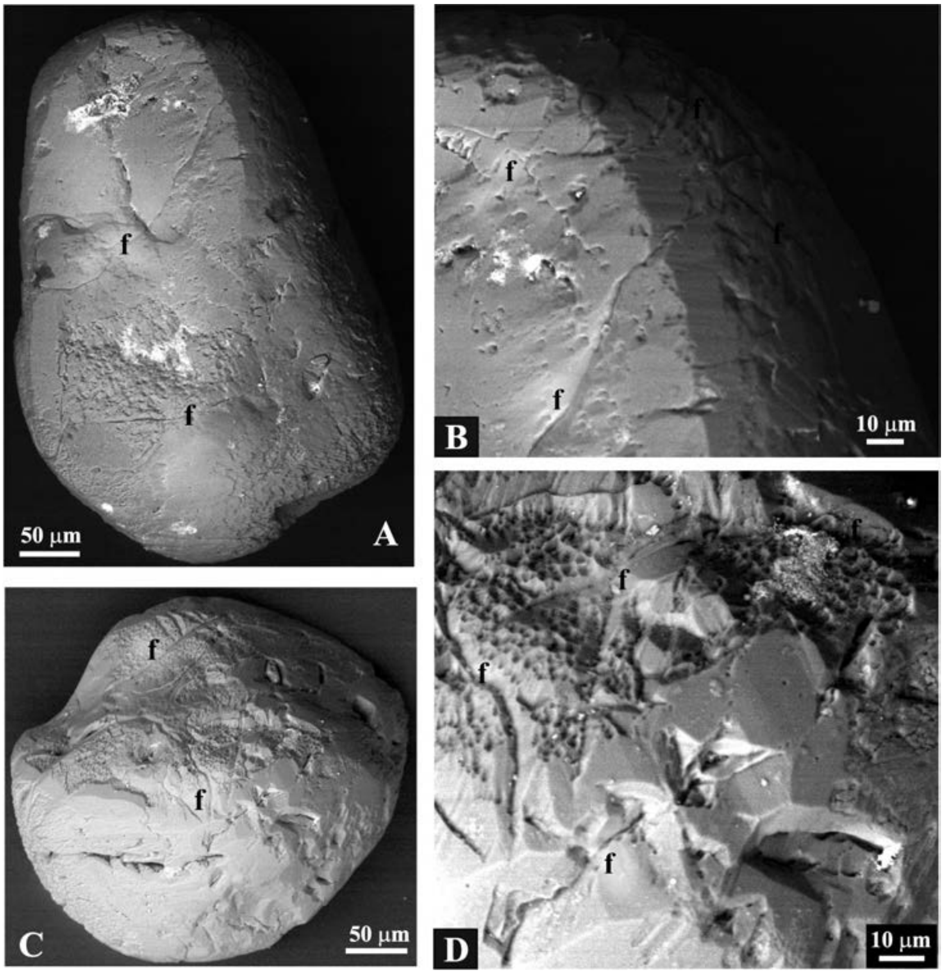

Fig. 6. Two sand quartz grains from Sablinka Formation. (A) Sub-rounded grain with two facets of crystalline overgrowth in the upper part and etching textures in the lower part. (B) The same facets with larger magnification. It is evident, that the facet angle has no signs of rounding, but etch pits are visible on the facets. (C) Rounded grain partially covered with crystalline overgrowth, with the other part showing etching textures. (D) Detail of grain C surface, enlarged. Letter (f) in the figure indicates the furrows

factors necessary for formation of mature pedogenic silcrete profiles: seasonal climate with high rates of evaporation and sufficiently long time (>10^6 years) [17]. A wide variety of pedogenic silcrete morphologies are known, formed over various rocks in different landscapes [17, 18], however only one, the most common variety, found in northern South Australia and western New South Wales, is relevant for our discussion. It is prismatic or columnar silcrete. Their vertical profile is characterized by the following sequence of structural zones, top—down: (1) loose sand; (2) pseudo-breccia and pseudo-conglomerate zone, with abundant granular or nodular concretions, very densely cemented with silica; (3) columnar zone with a system of polygonal sub-vertical block fractures; (4) granular zone with irregularly mixed rock patches with various degree of cementation [17]. The width of prismatic column varies from 25 cm to 2 meters; the height varies from 50 cm to 5 meters [19].

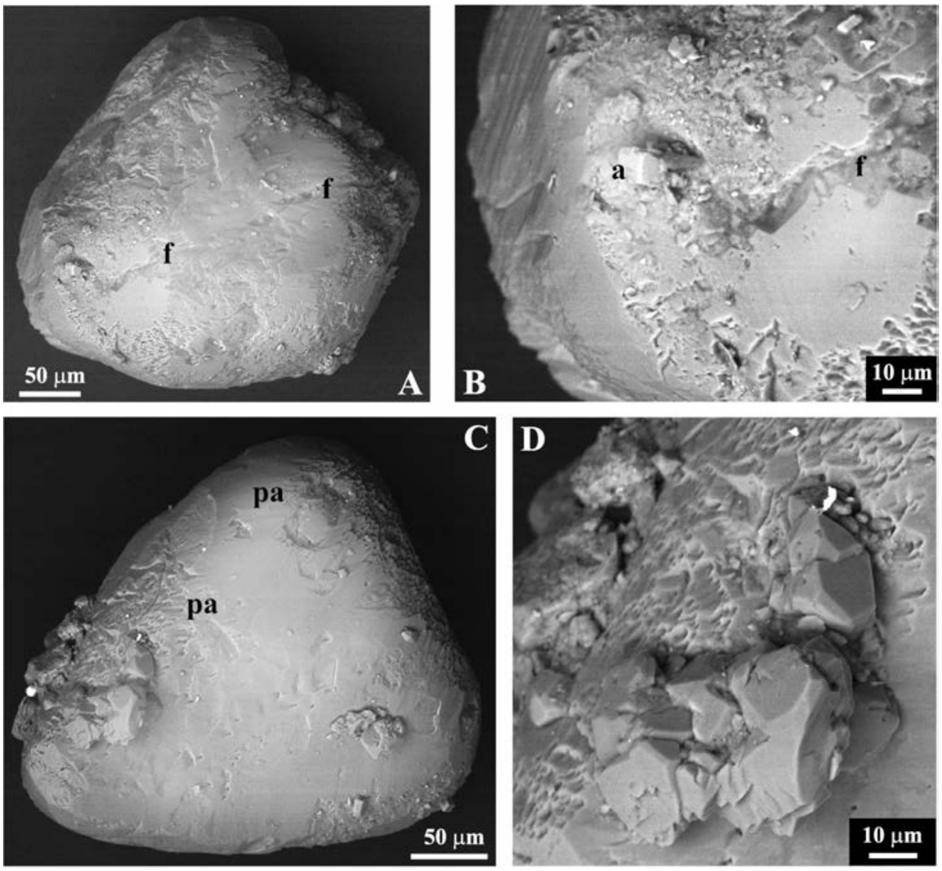

Fig. 7. Quartz grains from Sablinka Formation with adjacent incipient facets of crystalline overgrowth and chemical etching textures. (A) Sub-rounded grain with elongated etch furrows. (B) Part of A with large magnification. 3 fragmental facets of quartz crystal are visible. The flat facet to the right of the center has numerous additional smaller facets around fractures and dissolution pits. (C) Rounded low-spherisity "polished" grain mostly covered with thin crystalline overgrowth film, with adhesion of silt-sized quartz euhedra. (D) Group of silt-sized euhedra, with large magnification. Letters in the figure indicate: (a) ankerite crystal; (f) furrows; (pa) parabolic etch arches

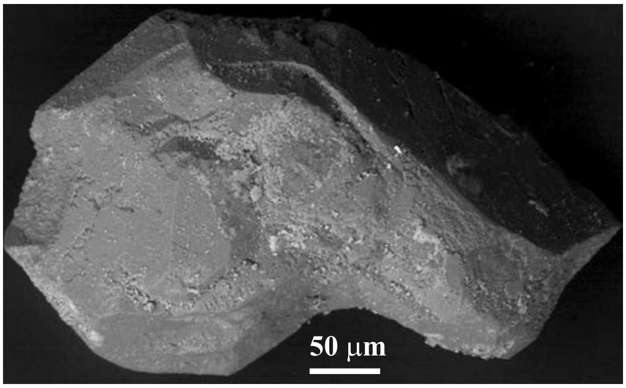

Fig. 8. Uncommonly shaped quartz grain, completely overgrown with crystalline facets from the top of the middle member of Sablinka Formation; possibly Japanese twin

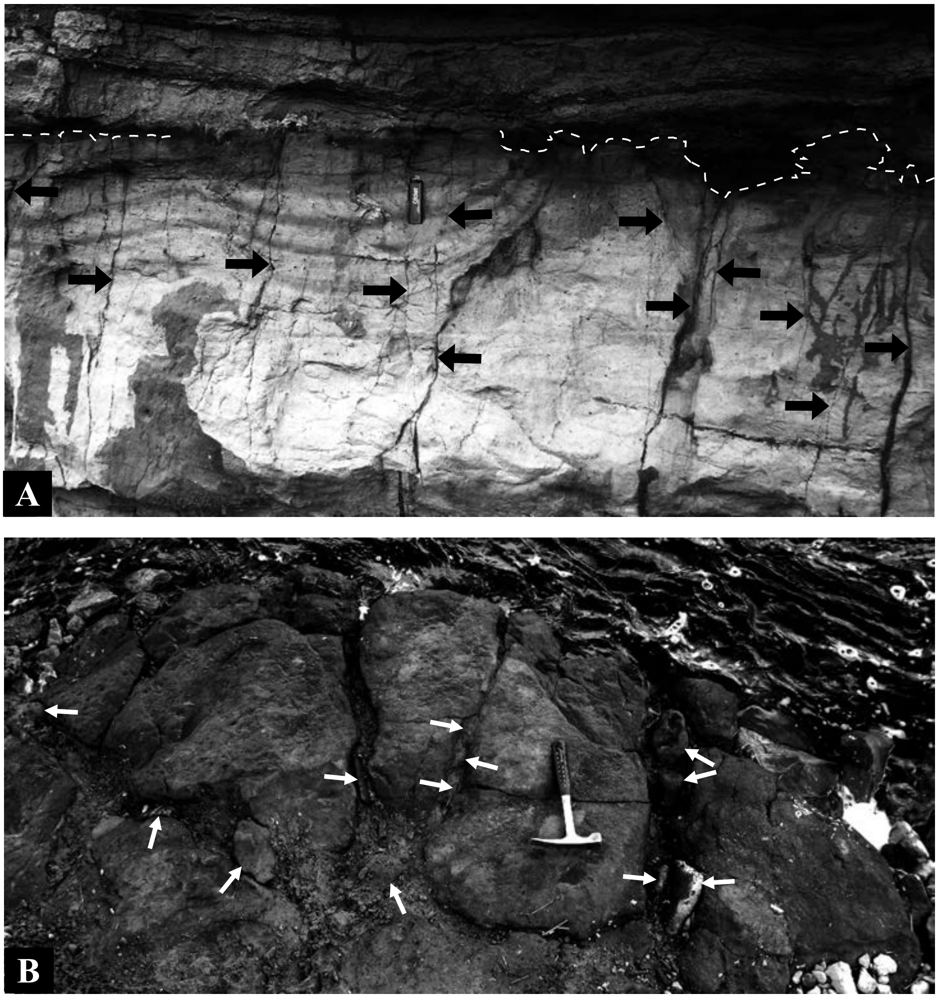

Fig. 9. Polygonal system of subvertical fractures at the top of Sablinka Formation, dividing the sandstones into prisms or columns. (A) Fractures (arrowed) in the vertical wall of the outcrop: erosional pockets in the openings of fractures are visible (dark areas). The boundary with the overlaying Ladoga Formation sandstones is shown as white dashed line. There are no large pebbles at the contact between formations, because they were removed and collected as samples by the students of the St. Petersburg State University. The lighter is shown for scale. (B) Fracture openings at the top of Formation exposed by the river. The fractures form a polygonal system, the openings are widened and filled with basal Obolus sandstone of Tosna Formation with sedimentary quartzite pebbles (arrowed). The infilling material is cemented with iron hydroxides. The hammer is 27.5 cm long

The similarity of the profile of pedogenic silcretes from South and East Australia to the features preserved in Sablinka Formation and the overlaying deposits is striking. Apparently, the irregularly shaped pebbles and cobbles with dense silica cement, and angular, pitted or hummocky surface from the basal layers of sandstones of Ladoga and Tosna formations, are redeposited concretions from Zone (2). However, they do not form a thick layer, which indicates insufficient development of this zone (Fig. 10). The sandstones at the top of Sablinka

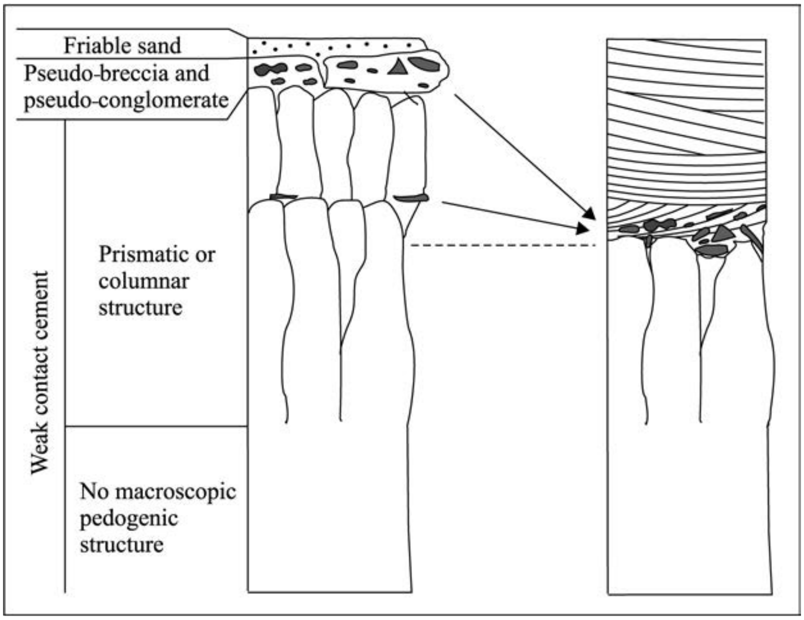

Fig. 10. Sketch of the full pedogenic silcrete profile at the top of Sablinka Formation (left) and the same profile after erosion during subsequent transgression (right). The sedimentary quartzite accumulations are filled with gray.

Formation, divided into columns by polygonal system of sub-vertical fractures, are identified as remaining bottom portion of Zone (3). The absence of the granular zone in Sablinka formation can be explained by high permeability of original sands, or insufficient time for formation of the zone.

According to the reconstructions by L. R. M. Cocks and T. H. Torsvik [20], the studied area during those distant times was located between 40° and 45° southern latitude.

Conclusions

Summarizing the results of our study, which originally intended only to systematize the surface textures of grains of Sablinka sandstones, we came to the following conclusions: formation of typical prismatic pedogenic silcrete profile took place at the top of Sablinka Formation at the Guzhangian—Furongian boundary. Silica redistribution process encompassed the entire section of the Formation, due to high permeability of the sandstones. However, the profile did not reach maturity during the lowstand period. The top portions were eroded and redeposited during the subsequent transgressions.

References

1. Rukhin L. B. The materials for the study of the condition of sedimentation and lithology of the *Obolus* series in the basin of Tosno and Sablinka. *Annals of Leningrad State University, Series of Geology and Soil Science.* 1939, issue IV, pp. 4–93. (In Russian)

2. *Geology of USSR. Vol. I. Leningrad, Pskov, and Novgorod Regions: Geological descriptions.* Eds V. A. Selivanova, V. S. Kofman. Moscow, Nedra Publ., 1971. 503 p. (In Russian)

3. Popov L. E., Khazanovich K. K., Borovko N. G., Sergeeva S. P., Sobolevskaya P. F. *The key sections and stratigraphy of the phosphate-bearing Obolus beds in the north-east of the Russian Platform*. Leningrad, Nedra Publ., 1989. 222 p. (In Russian)

4. Sliaupa S., Fokin P., Lazauskiene J., Stephenson R. A. The Vendian–Early Palaeozoic sedimentary basins of the East European Craton. *Geological Society*. London, Memoirs, 2006, vol. 32, pp. 449–462.

5. Kheraskova T. N., Andreeva N. K., Vorontsov A. K., Kagramanyan N. A. Evolution of the Moscow Sedimentary Basin in the Early Paleozoic. *Lithology and Mineral Resources*, 2005, vol. 40, no. 2, pp. 150–166.

6. Nielsen A. T., Schovsbo N. H. The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. *Earth-Science Reviews*, 2011, vol. 107, pp. 207–310.

7. Nielsen A. T., Schovsbo N. H. Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia. *Bulletin of the Geological Society of Denmark*, 2007, vol. 53, pp. 47–92.

8. Berthault G., Lalomov A., Tugarova M. A. Reconstruction of Paleolithodynamic Formation Conditions of Cambrian-Ordovician Sandstones in the Northwestern Russian Platform. *Lithology and Mineral Resources*, 2011, vol. 46, no. 1, pp. 60–70.

9. Khasanovitch N. K., Popov L. E., Melnikova L. M. Inarticulate brachiopods, ostracods (bradoriids), and hiolithelmints from Sablinka Formation of Leningrad Region. *Paleontological Journal*, 1984, vol. 4, pp. 33–47. (In Russian)

10. Dronov A., Miculáš R. Paleozoic Ichnology of St. Petersburg Region. *Excursion Guidebook. Translation of the Geological Institute*, 2010, vol. 596. 70 p.

11. Krinsley D. H., Doornkamp J. C. *Atlas of quartz sand surface textures*. Cambridge, Cambridge University Press, 1973. 91 p.

12. Mahaney W. C. *Atlas of sand grain surface textures and applications*. Oxford, U. K., Oxford University Press, 2002. 256 p.

13. Vos K., Vandenberghe N., Elsen J. Surface textural analysis of quartz grains by scanning electron microscopy (SEM): From sample preparation to environmental interpretation. *Earth-Science Reviews*, 2014, vol. 128, pp. 93–104.

14. Bull P., Morgan, R. Sediment Fingerprints: A forensic technique using quartz sand grains. *Science and Justice*, 2006, vol. 46, isuue 2, pp. 107–124.

15. Lehnert O., Calner M., Ahlberg P., Ebbestad J. O., Harper D. A. T., Meinhold G. Palaeokarst formation in the early Palaeozoic of Baltoscandia — evidence for significant sea-level changes in a shallow epicontinental sea. Eds A. Lindskog, K. Mehlqvist. *Proceedings of the 3 rd IGCP 591 Annual Meeting. Lund, Sweden, 9–19 June 2013.* Lund University, 2013, pp. 169–170.

16. Berner R. A. Atmospheric carbon dioxide levels over Phanerozoic time. *Science*, 1990, vol. 249, no. 4975, pp. 1382–1386.

17. Nash D. J., Uliot J. S. Silcrete. *Geochemical sediments and Landscapes*. Eds D. J. Nash, S. J. McLaren. Blackwell, Oxford, 2007, pp. 95–143.

18. Milnes A. R., Twidale C. R. An overview of silicification in Cainozoic landscapes of arid Central and Southern Australia. *Australian journal of soil research*, 1983, vol. 21, pp. 387–410.

19. Dixon J. C. Duricrusts. *Geomorphology of desert environments.* Eds A. D. Abrahams, A. J. Parsons. London, Chapman and Hall, 1994, pp. 82–105.

20. Torsvik T. H., Cocks L. R. M. Norway in space and time: A Centennial cavalcade. *Norwegian Journal of Geology*, 2005, vol. 85, pp. 73–86.

Статья поступила в редакцию 26 июня 2015 г.

Контактная информация:

Федоров Петр Владимирович — кандидат геолого-минералогических наук, доцент;
ordovician@yandex.ru
Палкина Алиса Ивановна — студент; st014887@student.spbu.ru

Fedorov P. V. — PhD, Associate Professor;
ordovician@yandex.ru
Palkina A. I. — student; st014887@student.spbu.ru